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TECHNIQUES FOR EVALUATING OPERATOR LOADING IN MAN-MACHINE SYSTEMS

A "Model" for Digital Simulation of One and Two-Operator Man-Machine Systems

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Prepared for
Engineering Psychology Branch
OFFICE OF NAVAL RESEARCH
Under Contract Nonr-2492(00)

Applied Psychological Services
Wayne, Pennsylvania

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Office of Naval Research
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ABSTRACT

A model, which had as its aim the prediction of the effectiveness of uni-operator man-machine systems, was previously derived and amplified by Applied Psychological Services. This previous model was tested against two independent tasks drawn from Naval aviation operating experience. Reasonable conformity was found between the predictions resulting from application of the model and operational experiences. The present report describes the extension of this model to simulate two-operator systems. The two-operator model may also be employed for evaluating uni-operator systems.

In Applied Psychological Services' two-operator model, a high speed digital computer is used to calculate and record simulated operator performance data (e.g., performance time, stress, etc.) for every action of each operator and to yield an indication of system effectiveness on the basis of these simulations. After development, the model was applied to the simulation of in-flight refueling of an F8U receiver aircraft by an A4D tanker aircraft. The maneuvers and actions of the F8U pilot during approach and probe insertion as well as the concomitant actions of the tanker aircraft pilot during this flight task were simulated.

The results from the model as reflected through the digital simulation were compared with empirical criterion data on actual in-flight refueling success and were further evaluated on the basis of their compatibility with logical expectation. The results from this initial application of the model, presented and evaluated in this report, appear to conform with reality and are generally reasonable. Further validation of the model is required to determine the range and limits of its generality.

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TABLE OF CONTENTS

TABLE OF TABLES

TABLE OF FIGURES

CHAPTER I

INTRODUCTION

Complex systems in which a human is expected to operate his machine are often found to overburden or underburden the operator after the system is accomplished. This report presents the results of the third in a series of studies by Applied Psychological Services directed toward the general goal of developing methods for predicting such system design mismatches while man-machine systems are in the early design stage. The first two reports of this series (Siegel and Wolf, 1959a; Siegel and Wolf, 1959b) described the development and application of a psychological-mathematical model which enables the simulation of single operator machine systems. The present report describes the extension and application of this model to the situation in which a machine, subsystem, or system is operated simultaneously by a team of two individuals[1].

Purposes of Model

It is the purpose of this model to give equipment designers quantitative answers, while equipment is in the early design stage, to questions such as the following:

1. Given a selected machine design, can an average two-man team be expected to complete successfully all actions required for task performance within the time limits given for each operator?

1. The major similarities and differences between the one- and two-man models are given in Appendix A.

2. How does task or system success probability change for slower or faster teams and longer or shorter periods of allotted time?

3. How great a relative stress is placed on each operator during his performance and in which portions of the task are the operators overloaded or underloaded?

4. What is the frequency distribution of each operator's failures as a function of various relative stress tolerances and team member speeds?

5. For how much time is each operator idle while waiting either for the other operator or for some outside event to occur?

Use of the model is based on the high-speed, general purpose digital computer. The computer operates on source data concerning performance by average operators and on system parameters; using these it simulates each operator by calculating values for and keeping track of items such as his performance time, subtask and task success or failure, stress, and idle time. The speed of arithmetic computation, capacity for storing information and the flexibility of decision making offered by such computing devices enabled the computer, in approximately 3.2 seconds, to simulate the maneuvers and actions of a buddy system in-flight refueling operation which normally is completed by the two pilots in approximately 70 seconds. This task consists of 13 subtasks for the pilot of the tanker aircraft and 27 subtasks for the pilot of the receiver aircraft. The task was simulated a total of 4,400 times by the computer, representing 44 combinations of pilot types and conditions.

Other Approaches

Alternative approaches to the problem of simulating man-machine systems have been taken elsewhere. Pondy (1959) attempted to present a brief description of a sample of the existing unclassified methods. In that summary, which presented only those techniques based on quantitative methods, the following recommendation (Hopkins and Williams, 1958) was presented:

> "...initial systems approaches should not be expected to be accurate quantitative predictions. We do not yet know enough about general systems behavior for this to be possible. Rather, systems models will probably aid in making qualitative predictions and providing the mathematical, conceptual, and linguistic framework for describing systems behavior realistically and unambiguously."

Pondy decries the deficiencies of available models which:

a. ignore the question of measuring or defining good performance

b. present a distinction between man and machine when it should be absent

c. are based on a methodology which requires a new restricted model to be worked out for each new problem

While it must be clearly admitted that no universally applicable man-machine simulation model now exists, the above statements indicate a more pessimistic picture than is warranted by the present situation. The field is being explored by a number of individuals and organizations from a variety of approaches.

One approach is to derive the mathematical representations for an operator's performance, learning effects and the like in a specific task situation. The result of this approach would be a model which is not a description of human behavior, but a description of a particular system in which the human plays a part. And the model may not be applicable outside of the specific class of the man-machine task selected. In such a model, the human may be represented as a linear amplifier or other servo element in the control loop; random noise, possibly independent of the input, is sometimes assumed together with constant reaction time.

Another approach to simulating the human is that of Powers, McFarland and Clark, as reported by Mowrer (1960). This approach considers human feedback systems as a "...hierarchical assembly of feedback systems in which control is accomplished thru a higher system's setting the reference levels for lower systems." Powers and his co-workers believe this model to be "...an organizing principle, an overall description of human organization, that may lead to some of the needed basic theory..."

It is at this point that the present authors become confused in trying to think through the work of Powers *et al.* It seems that a descriptive model should be built from and based on behavior theory. Behavior theory should not be forced into or squeezed out of the mold of an electronic or mechanical model.

Another approach is based entirely on probability theory, possibly extended as a function of time. In this case, analytic expressions are derived for the probability of successful task completion as a function of subtask success probabilities and subtask criticality. Thus, the quantitative results are given for the system as a whole and provide little other information on task relevant parameters such as points of stress, waits or delays, or operator variations.

Basic studies, initiated in the relatively new study of bionics, may be expected to be eventually applicable to a more versatile and accurate prediction method for man-machine systems. Bionics may be defined as the science of applying the knowledge of biology and biological techniques to the design of electronic devices. Perceptron mechanisms, neuron simulation, pattern recognition and decision making are areas now being studied by pioneer bionic researchers. The results of these studies may, in the future, permit a realistic simulation of human behavior through extensive biological simulation.

The Applied Psychological Services' model is not based on transfer functions, nor is it wholly dependent upon probability theory. It consists, rather, of a combination of techniques. The model provides quantitative results for the critical problems of task success probability and points of high stress and also yields the required interpretive data such as:

1. the peak and terminal stress levels and on which subtask they occurred

2. identification of non-critical subtasks skipped by an operator due to his high stress

3. identification of waiting or idle times

Analogue *vs*. Digital Simulation

We note that the application of an analogue computer to the feedback control loop model is logical since this type of computer operation depends on establishing a system whose properties are electrically or mechanically analogous to the properties of the equations or the model under study. On the other hand, the digital computer is capable of much greater precision than the analogue type. While the analogue computer is applicable to a wide range of control and feedback problems, the digital computer is more directly suited to those models whose implementation is based on the calculation of discrete quantities rather than continuous variables. The digital calculators are particularly well suited to simulating the decision making required by operators; they are quickly adapted from problem to problem, are flexible, and readily available.

CHAPTER II

THE MODEL

Use of the Model

Prior to the use of the model, an analysis is performed for the man-machine system under consideration. The performance of each operator is arranged into ordered, discrete actions called "subtasks" and for each subtask certain specific required source data are compiled. These data, together with the selected parameter values (e.g., the time allotted for performance), are prepared in punched card form and introduced into the digital computer for which a computer program has been prepared. As directed by its program, the computer will sequentially simulate, according to the rules of the model, the performance of each operator in the team on each subtask. The simulation, consisting basically of stress, urgency, subtask execution time, and subtask success calculations, plus the proper bookkeeping, continues serially for each subtask performed by each operator. The normal sequence of subtasks, whether linear or non-linear, may be modified with complete generality in the event that actions must be skipped or repeated due to operator failure on any subtask or as a result of operator decisions. A simulation is completed when the simulated operators run out of allotted time or successfully complete the task. During the course of the computer's "performance" of the task, results are recorded by the computer on magnetic tape, and these data are later printed to indicate the areas of operator overload, failure, idle time, high stress, etc., for the given set

of selected parameters. Numerous repetitions of the task with different parameter values yield additional records and printouts. Frequency distributions, summarized, and reduced data are provided automatically by the computer, if desired. Performance graphs and charts are then prepared from these data. If alternate designs are indicated as a result of the analysis of the resulting data, the new designs are similarly prepared and analyzed in order to determine the extent of improvement brought about by the modifications.

The basic flow chart for the model is presented as Figure 1. This figure displays the logical computation sequence performed by the computer during the simulation. The subscript i is used to identify the subtasks which comprise the total task mission. The operators are denoted by j and j' which may assume values of 1 or 2, where j denotes either operator specifically and j' denotes the other operator. The simulation is completed only after both operators complete the necessary sequences of subtasks.

- 8 -

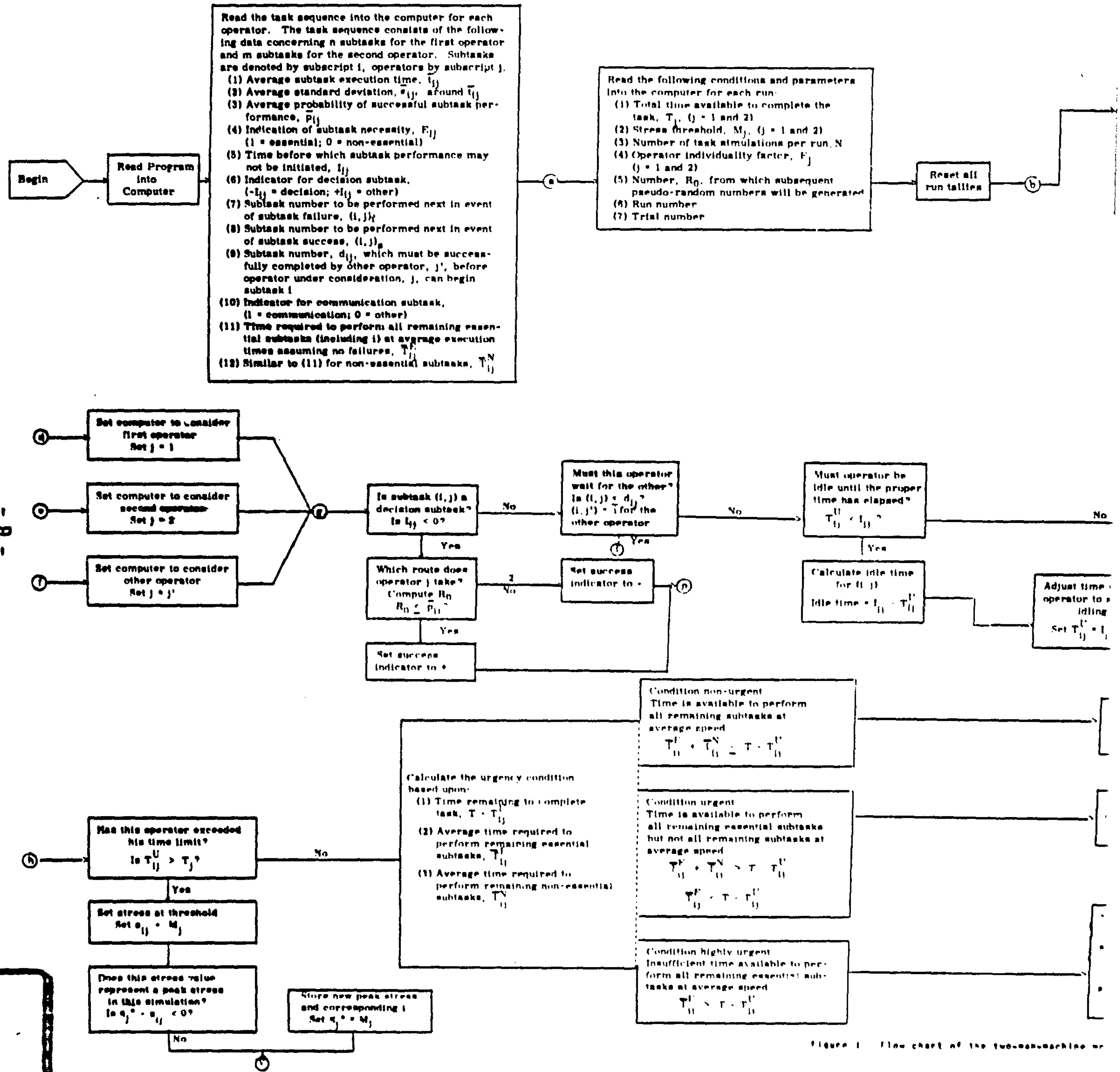
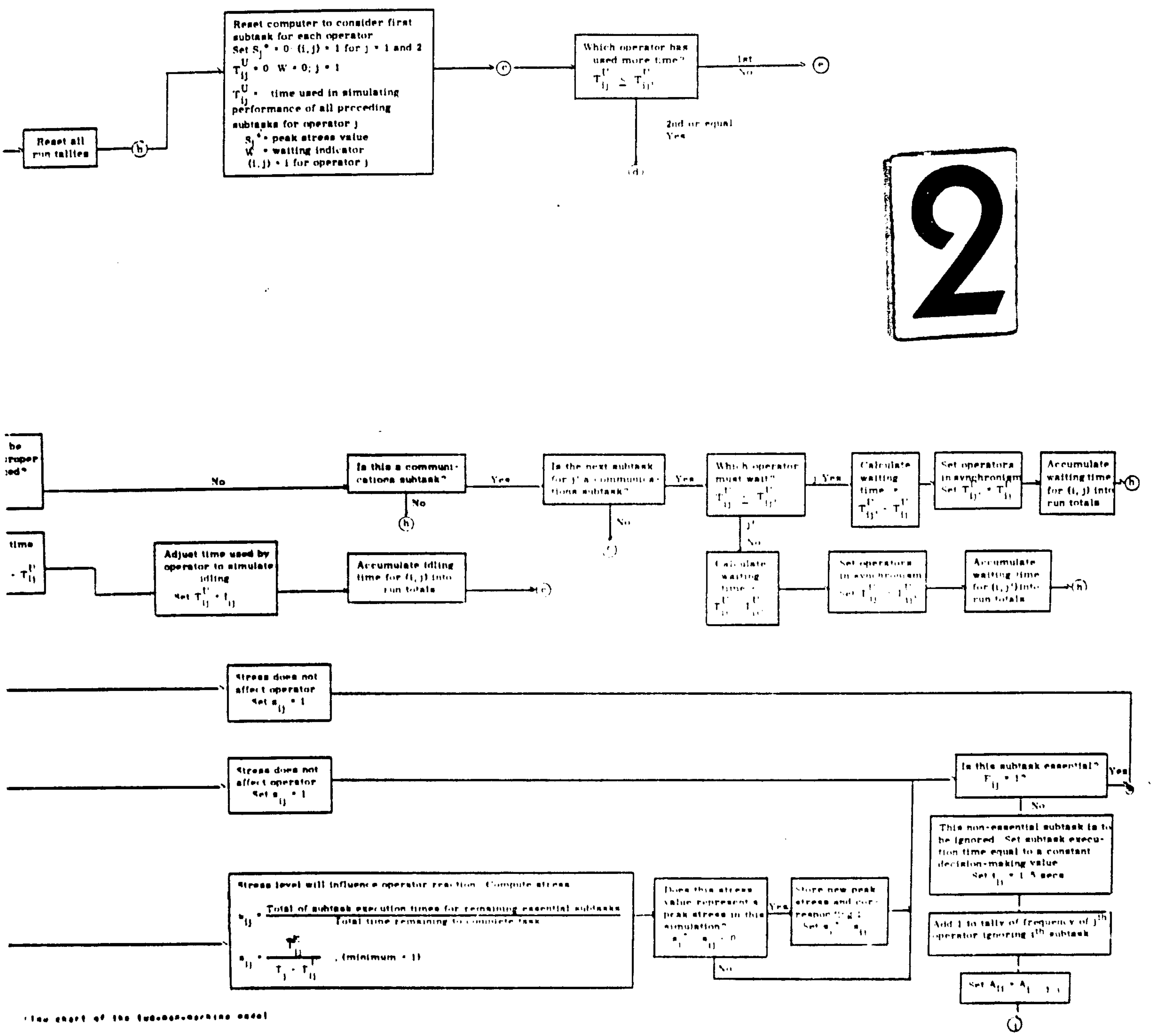


Figure 1 Flow chart of the two-man-machine m



Flow chart of the man-machine model

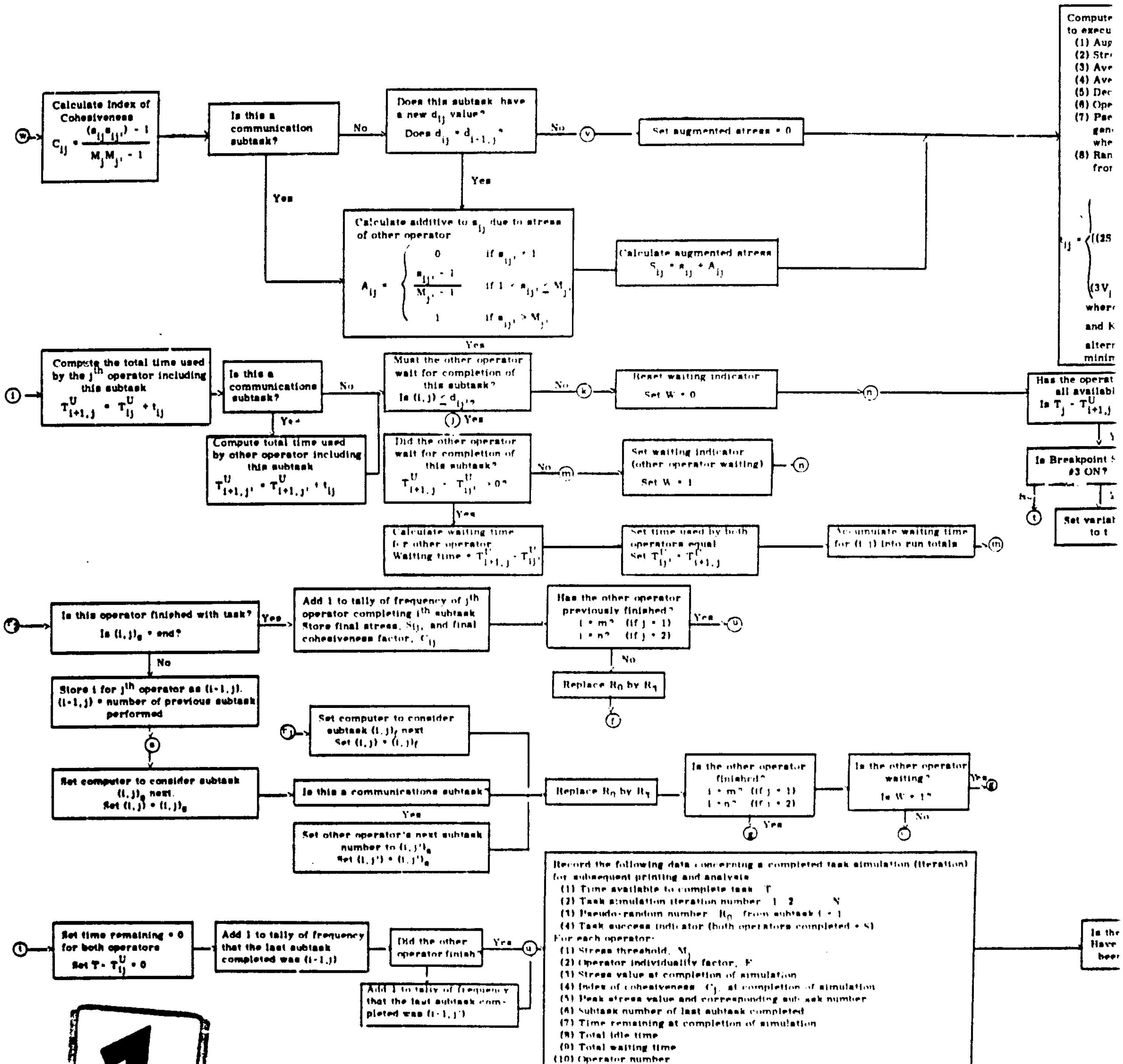


Figure 1 (Cont.)

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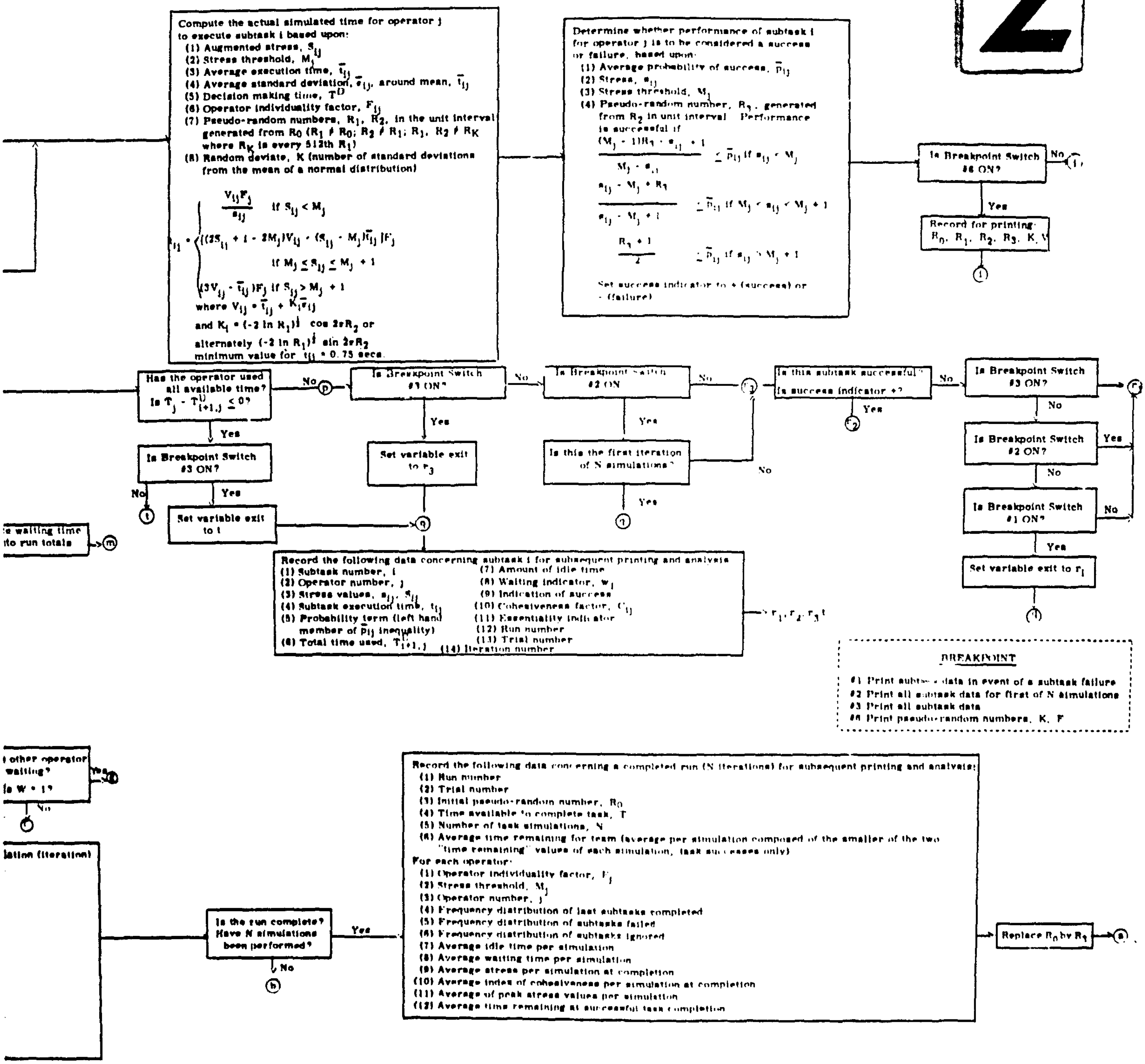


Figure 1 (Cont.)

Input Data, Parameters, and Initial Conditions

Following the reading by the computer of its coded instructions, the basic subtask input data are read and stored in the computer's memory. As shown in Figure 1, twelve items of subtask input data exist for each subtask ($i = 1, 2, \ldots, n$), and each operator ($j = 1, 2$). These subtask data may be derived from such procedures as task analysis, literature search, and personal interviews. The required input data for each operator are:

1. average subtask execution time, $\bar{t}_{ij}$, the average time required by the j^{th} operator to perform subtask i. This average value represents the case in which the operator is under no stress. Values applicable for most subtasks have been derived and presented previously by Siegel and Wolf (1959a).

2. average standard deviation, $\bar{\sigma}_{ij}$, under the no stress condition taken around the $\bar{t}_{ij}$, for the average operator. Values for these data have also been previously derived and presented by Siegel and Wolf (1959a).

3. average subtask probability, $\bar{p}_{ij}$, that the average operator, j, under no stress can perform subtask i successfully.

4. indication of subtask essentiality, E_{ij}, an indicator specifying whether or not the successful performance of subtask i by operator j is essential to successful completion of the task. This datum, derived from task analytic information, allows the computer to ignore non-essential subtasks during certain "highly urgent" conditions.

5. idle time requirement, I_{ij}, the point in time before which operator j is not permitted to begin subtask i.

6. indication of whether subtask i is a decision subtask or a normal action subtask; the sign of I_{ij} is used as the indicator. A decision subtask is an artificial subtask used to enable the computer to simulate an operator's decision-making processes.

7. subtask number, $(i, j)_f$, to be performed next by operator j in the event of failure of subtask i, or in the event the operator chooses the first of two alternate courses in a decision subtask.

8. subtask number, d_{ij},(mnemonic delay) which must be successfully completed by the other operator (operator j') before operator j can begin subtask i. By proper selection of d_{ij} values, it is possible to cause either

simulated operator to "wait" until his partner has completed a stipulated subtask successfully. Thus, "waiting" for one's partner is simulated differently from time spent "idling" until a fixed time event elapses as in 5 above.

9. subtask number, $(i,j)_S$, to be performed next by operator j in the event he succeeds on subtask i, or in the event he chooses the second alternate course in a decision subtask.

10. indication of whether or not subtask i for operator j is a subtask in which the operators communicate with each other.

11. time, T_{ij}^{E}, required to perform all remaining essential subtasks (including i) at average execution times, assuming no failures. With no branching or decisions, $T_{ij}^{E} = \sum_{k=i}^{n} \bar{t}_{kj}$.

12. time, T_{ij}^{N}, required to perform all remaining non-essential subtasks (including i) at average execution times, assuming no failures.

The other main set of data required by the computer in advance of the simulation consists of the parameters and initial conditions discussed below. These are inserted to permit the adjustment of critical variables and the consequent determination of the range of their effects.

Initial Conditions and Parameters

The number of times, N, that a given task is to be simulated by the computer is the first initial condition inserted into the computer prior to the computation for a given task. In order to simulate intra and inter-individual performance differences, the simulation of any individual subtask is based, in part, on a random effect. Because of this stochastic effect, it is necessary to repeat the simulation of a task many times in order to obtain sufficient performance data for each set of conditions. Thus, there are N simulations (or N iterations) per computer "run."

Another initial condition is R_0, the number from which the computer generates subsequent pseudo-random numbers needed during the course of the simulation. The R_0 selected for the first pseudo-random number in the first run is 123456789. Subsequently, the last pseudo-random number generated in one run is used as the first value in the next run.

Parameters are those initial conditions, selected prior to a computation, which may be varied in order to evaluate either the model or a man-machine system. The stress thresholds, M_j, one for each operator,

are examples of such parameters. The stress threshold may be considered as the operator's breaking point. For example, an M_j value of 2.0 indicates that the operator begins to become slower and less accurate at the point at which he has more than twice as much to do (at average speed) as he has time available. Prior to this point, any added backlog of essential subtasks creates a mental inducement of stress which affects operator actions so that they become faster and more accurate. For any given run of N iterations or simulations, a specific stress threshold is used in the calculations. The effects of a change in M_j are studied by performing runs in which these parameters assume different values.

The parameters, T_j $(j = 1, 2)$, are the total times allotted to each operator for task performance. Various computer runs may be performed to determine the effect of a change of these parameters. This facility is provided since the T_j value may not be known exactly in systems which are proposed or designed but not yet built. In a two-man team model, the task can be considered to have been successfully completed if both operators complete all required subtasks within the time specified by the larger of the two values.

The parameters, F_j, which account for variance among individuals, are the individuality factors for the two operators. This provides the ability to simulate an operator who usually performs faster or slower than the average operator. F_j possesses a value of unity for the average operator. The effect of faster, or more highly motivated operators $(F_j < 1)$, and

slower operators ($F_j > 1$) in the performance of the task is examined by performing several computer runs with different values for these multiplicative factors.

A run number is used to identify runs and a trial number is inserted to identify later continuations of a particular run in which all parameters and initial conditions are identical except R_0. This enables replication on the same basic operators. The trial number and run number are retained for identification and subsequent analysis.

In summary, for a given run and trial, starting with R_0 as the first pseudo-random number, N simulations of a single task are performed by the computer with fixed values for each of the parameters M_j, T_j, and F_j.

The Simulation Sequence

The digital computer is a sequential device which performs individual operations at very high speeds. Having stored the program, parameters, and initial conditions, the computer begins processing these data in accordance with the logic presented as Figure 1.

For either operator and for any given subtask after the first, the computer determines which subtask to perform next in accordance with $(i,j)_s$ and $(i,j)_f$ input data. The computer's determination of which operator to simulate at any given time in the sequence depends upon the amount of time used by the operators. In Figure 1 (circled c), T_{ij}^U indicates the total time used up by operator j while "performing" all subtasks from the start of the simulation through subtask i-1. The operator having the smaller T_{ij}^U value is selected, and his next subtask is simulated.

Having elected to simulate subtask i for operator j, the I_{ij} (decision) input is examined. If the sign of I_{ij} is negative, then the subtask is a decision subtask (discussed later). Otherwise, the computer proceeds to determine whether operator j must wait for his partner before performing subtask i. If waiting is required, the sequence recycles to the circled f on the flow chart and the data for the other operator (j') are placed in proper storage for processing and the sequence continues. If waiting is not required, then a determination is made as to whether operator j must idle until I_{ij} simulated seconds have elapsed from the beginning of the simulation. If idling is required, the idle time $I_{ij} - T_{ij}^U$ is recorded,

totals accumulated, T_{ij}^{U} set equal to I_{ij}, and the control returned to the circled c to determine which operator to simulate next. If no idling is required, a determination is made of whether or not subtask i is a communication subtask. If so, to synchronize the operators in time, the total time used by both operators is set equal to the larger value. This act may result in a wait for either operator and is treated as the wait described above. Following the synchronization of the operators, or in the event the subtask was not a communication subtask, control is transferred to the circled h of Figure 1.

Urgency and Stress

Next, one of three states of "urgency" is determined. Urgency is based upon the remaining time available to operator j for completing the task and the average time required to complete it.

(1) The situation is non-urgent when (assuming average speed and no operator failures), on the average, sufficient time remains for an individual operator to complete all remaining subtasks. Thus, the non-urgent state exists during performance of subtask i when

$$\bar{\bar{T}}_{ij}^{E} + \bar{\bar{T}}_{ij}^{N} \leq T_j - T_{ij}^{U}$$

(2) The urgent state occurs for either operator whenever insufficient time is available for completing all remaining subtasks, provided that sufficient time is available to complete all remaining essential subtasks. That is, the situation is urgent if:

$$\bar{\bar{T}}_{ij}^{E} + \bar{\bar{T}}_{ij}^{N} \geq T_j - T_{ij}^{U} \text{ and}$$

$$\bar{\bar{T}}_{ij}^{E} \leq T_j - T_{ij}^{U}$$

These are based on estimated average operator execution times and the assumption that no operator failures will occur. In this situation the non-essential subtasks are ignored by the computer.

(3) The situation is highly urgent if there is insufficient time available for completing even the remaining essential subtasks at average operator speeds, i.e., when

$$\overline{\overline{T}}_{ij}^{E} > T_j - T_{ij}^{U}$$

Similarly, in this urgency state non-essential subtasks are ignored by the computer.

Following the determination of the urgency condition, the stress condition is calculated for operator j in his simulated performance of subtask i.

The "certainty" in the operator's "mind" that there is insufficient time remaining to complete the essential subtasks (when performing at normal speed and efficiency) will impress a state of stress on the operator. The model defines stress, s_{ij}, as a state of mind of operator j just prior to his performance of subtask i. Current psychological theory suggests that emotion or stress up to a certain point acts as an organizing agent on behavior; beyond this point stress acts as a disorganizing agent. Accordingly, the model recognizes an organizing effect on operator performance as long as s_{ij} is less than M_j, where M_j is a threshold value; if s_{ij} equals or exceeds M_j, the effect is disorganizing. During non-urgent and urgent conditions s_{ij} is defined to be equal to unity; when the situation is highly urgent, stress is defined as the ratio of the sum of the average remaining essential subtask execution times to the total time remaining:

$$s_{ij} = \frac{\overline{\overline{T}}_{ij}^{E}}{T_j - T_{ij}^{U}}$$

Thus, basic stress is the ratio of how much is left to do, to the amount of time available in which to do it.

Table 1 summarizes the conditions for urgency and stress as incorporated into the model. Non-essential subtasks are ignored during urgent and highly urgent conditions.

Table 1

Summary of Urgency and Stress Conditions

Urgency	$\frac{\overline{T}_{ij}^{E} + T_{ij}^{N}}{T_j - T_{ij}^{U}}$	$\frac{\overline{T}_{ij}^{E}}{T_j - T_{ij}^{U}}$	Condition (assume average operator)	Result	Stress
Non-urgent	≤ 1	≤ 1	Time is available to perform all remaining subtasks	Perform this subtask	1
Urgent	> 1	≤ 1	Time is available to perform all remaining essential subtasks but not all remaining subtasks	Ignore this subtask if non-essential	1
Highly urgent	> 1	> 1	Time is not available to perform all remaining essential subtasks	Ignore this subtask if non-essential; compute stress	$\frac{\overline{T}_{ij}^{E}}{T_j - T_{ij}^{U}}$

Team Cohesiveness

A feature has been included in the two-man team model to account for the effect of each operator's confidence in or cohesiveness with the other. This feature attempts to simulate the confidence of one operator in his partner. Team cohesiveness may also be reflective of disagreements in goals and/or their importance, methods, or locus of authority. An operator can often tell how well his partner is performing. When one operator "feels" that his partner is performing satisfactorily, it is assumed that the "peace of mind" this creates will enable him to perform normally, i.e., his execution times will depend on his own stress value, stress threshold, and other factors as previously described. On the other hand, if a partner is performing poorly, it might be expected that the knowledge of this poor performance will cause the first operator to modify his actions. The model causes faster or slower than normal execution times by one operator if he knows his partner is in a highly urgent situation. This is accomplished by causing the computer to add to the stress value of operator j if operator j' has a stress value greater than unity. Specifically, an additive A is calculated as follows:

$$A = \begin{cases} 0 & \text{if} \quad s_{ij'} = 1 \\ \dfrac{s_{ij'} - 1}{M_{j'} - 1} & \text{if} \quad 1 < s_{ij'} \leq M_{j'} \\ 1 & \text{if} \quad s_{ij'} > M_{j'} \end{cases}$$

The value of A is added to the individual stress value, s_{ij}, due to a single operator alone and the result, S_{ij}, is used in later calculations of subtask performance time, t_{ij}. In cases where direct visual contact between two operators is limited or absent, one operator may be correspondingly limited in his ability to discern the effectiveness of his partner's performance. With a further reduction in avenues of communication between operators (as, for example, where radio silence is maintained), a greater limitation is to be expected in the knowledge of one operator concerning the state of being of the other. Under such conditions, however, an operator can gain some knowledge of the efficiency of his partner's performance through subtasks which require waiting (simulated by d_{ij} values). Thus, if operator j cannot continue the execution of his required actions until operator j' has completed subtask i, and if operator j' is late in performing that subtask, operator j now has some basis for knowing (or assuming) that his partner is functioning poorly to some degree. This knowledge, in turn, will affect operator j's performance through the additive, A. Therefore, in certain two-man team tasks (and in the one here reported), the additive is computed only for those subtasks requiring waiting (either communication subtasks or those for which the d_{ij} value differed from the previous value).

In addition, an index of cohesiveness, C_{ij}, is also calculated for each operator on each subtask as a measure of the joint stress condition of the team. It is the product of the stress levels of the two operators normalized by their respective stress threshold values:

$$C_{ij} = \frac{(s_{ij} s_{ij'}) - 1}{(M_j M_{j'}) - 1}$$

When neither operator is under stress, then C_{ij} assumes a value of zero. Should both operators have a stress value equal to their thresholds, then C_{ij} assumes a value of unity. Thus, increasing C_{ij} values indicate greater team discontinuity due to increased stress.

Subtask Execution Time

Next, the execution time of the subtask is computed. The average operator will require $\bar{t}_{ij}$ seconds to perform subtask i when s_{ij} equals unity. In this case, his average standard deviation will be $\bar{\sigma}_{ij}$. Of course, no two operators would be expected to perform any subtask in exactly the same time on each repetition, and no operator would be expected to perform the same task identically over two occasions except by chance. For each subtask, it is assumed that the actual subtask execution time, t_{ij}, for the specific subtask, i, is normally distributed with mean dependent on $\bar{t}_{ij}$ and standard deviation dependent on $\bar{\sigma}_{ij}$. The computation of a reasonable and realistic specific value for the actual execution time, t_{ij}, for each subtask is made on the basis of a random selection from a normal distribution limited from below by a fixed minimum, selected as 0.75 seconds. The computer accomplishes the selection of t_{ij} by a random or Monte Carlo technique. Pseudo-random numbers R_1 and R_2 uniformly distributed in the unit interval

are sequentially generated from R_0 by the computer using the power residue method as described in an IBM manual (1959) and summarized in a subsequent section of this chapter. By the use of these independent random numbers, corresponding values of an independent random variable are generated having a distribution function equivalent to that of the normal distribution (i. e., normal deviates). This is done by the "direct" technique described by Box and Muller (1958) and evaluated by Muller (1959), and also discussed in a subsequent section of the present chapter.

Thus, if K_{ij} is the number of standard deviations from the mean corresponding to the random numbers generated in simulating subtask i for operator j, then the actual time of execution simulated by the computer, t_{ij}, is given by:

$$t_{ij} = \begin{cases} \dfrac{\bar{t}_{ij}}{S_{ij}} + \dfrac{K_{ij}\bar{\sigma}_{ij}}{S_{ij}} F_j & \text{if} \quad S_{ij} < M_j \\ [\bar{t}_{ij}(S_{ij} + 1 - M_j) + K_{ij}\bar{\sigma}_{ij}\,(2S_{ij} + 1 - 2M_j)]\,F_j & \text{if} \quad M_j \leq S_{ij} \leq M_j + 1 \\ [2\bar{t}_{ij} + 3K_{ij}\bar{\sigma}_{ij}]\,F_j & \text{if} \quad S_j > M_j + 1 \end{cases}$$

where F_j is the individuality factor described previously in this chapter. To effect these calculations from a computed value of K_{ij}, a linear change of variables is made through the calculation of $V_{ij} = \bar{t}_{ij} + K_{ij}\bar{\sigma}_{ij}$, which is normally distributed. The above expressions may then be put in the form:

$$t_{ij} = \begin{cases} \dfrac{V_{ij}F_j}{S_{ij}} & \text{if} \quad S_{ij} < M_j \\ [(2S_{ij} + 1 - 2M_j)\,V_{ij} - (S_{ij} - M)\bar{t}_{ij}]\,F_j & \text{if} \quad M_j \leq S_{ij} \leq M_j + 1 \\ [3V_{ij} - \bar{t}_{ij}]\,F_j & \text{if} \quad S_{ij} > M_j + 1 \end{cases}$$

The effect of the above is to provide a $\overline{t}_{ij}$ value, as shown in Figure 2, in which the values of $\overline{t}_{ij}$ and $\overline{\sigma}_{ij}$:

(1) are used unchanged when stress equals unity

(2) are decreased with increasing stress until stress assumes the threshold value

(3) are used unchanged when stress equals the threshold value

(4) are increased linearly with increasing stress beyond M until, when stress equals M > 1, the contributions of $\overline{t}_{ij}$ and $\overline{\sigma}_{ij}$ remain constant at $2\overline{t}_{ij}$ and $3\overline{\sigma}_{ij}$ respectively.

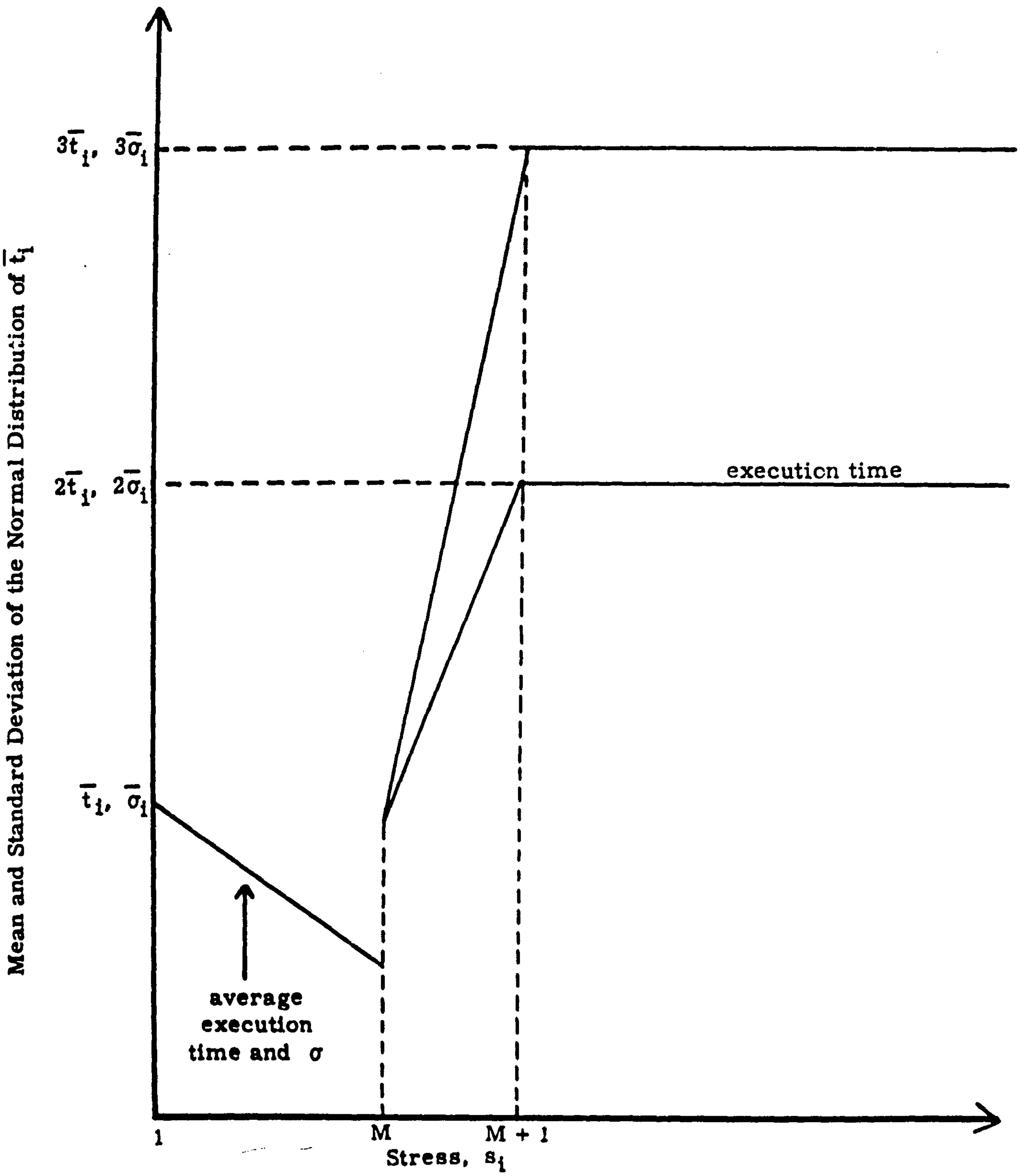


Figure 2 Average execution time and its standard deviation as functions of stress

Subtask Success and Failure

An average probability of successful performance for subtask i, $\bar{p}_{ij}$, is given as an input for each subtask. In the model, it is assumed that the actual probability of successful performance of a given subtask, p_{ij}, is a function of $\bar{p}_{ij}$, s_{ij}, and the threshold, M_j, as follows:

$$p_{ij} = \begin{cases} \bar{p}_{ij} + \dfrac{(1 - \bar{p}_{ij})(s_{ij} - 1)}{M_j - 1} & \text{if} \quad s_{ij} < M_j \\ \bar{p}_{ij}(s_{ij} + 1 - M_j) + (M_j - s_{ij}) & \text{if} \quad M_j \leq s_{ij} \leq M_j + 1 \\ 2\bar{p}_{ij} - 1 & \text{if} \quad s_{ij} > M_j + 1 \end{cases}$$

A review of Figure 3 which displays this function indicates that the probability of success increases linearly with stress until the stress threshold is reached. At this point, the probability assumes the average value, $\bar{p}_{ij}$, after which it decreases lincarly until, when stress has a value equal to $M_j + 1$, it levels off at a value which is decreased from $\bar{p}_{ij}$ by an amount equal to $1 - \bar{p}_{ij}$. In order to determine actual success or failure for any subtask, the computer generates a pseudo-random number, R_3, from R_2 according to the method described later in this chapter. The value of R_3 is thus uniformly distributed over the unit interval. The subtask is considered to have been performed successfully if R_3 is less than p_{ij}; otherwise, it is assumed that the operator failed to perform the subtask properly. This implementation indicates a failure with probability, p_{ij}, in the long run. To facilitate the calculation, these expressions were rearranged to indicate success if:

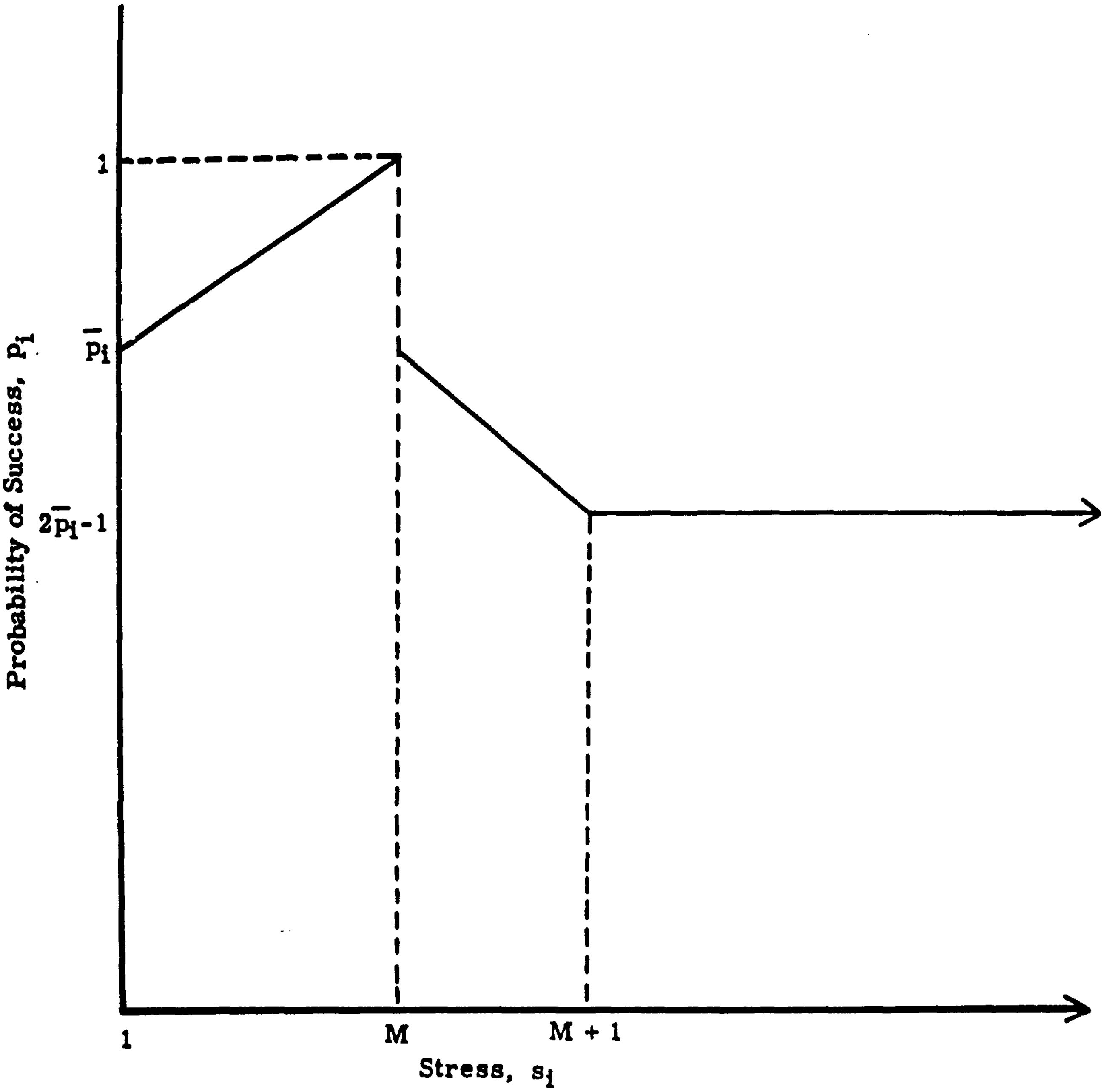


Figure 3 Probability of subtask success as a function of stress

$$\frac{(M_j - 1)R_3 - s_{ij} + 1}{M_j - s_{ij}} < \bar{p}_{ij} \qquad \text{when } s_{ij} < M_j$$

$$\frac{s_{ij} - M_j + R_3}{s_{ij} - M_j + 1} < \bar{p}_{ij} \qquad \text{when } M \leq s_{ij} \leq M + 1$$

$$\frac{R_3 + 1}{2} < \bar{p}_{ij} \qquad \text{when } s_{ij} > M + 1$$

The computed left hand member of these inequalities is called the probability term and is made available as a printed result. In event of either success or failure, input information indicates the subtask which is performed next.

Decision Subtasks

If the test for I_{ij} indicated a negative result, then the subtask is a decision subtask, i.e., a subtask in which the operator makes a decision. The purpose of this type of subtask is to simulate the real world by providing for possible task execution in other than a straight, linear sequence. For example, an operator may find it desirable to skip one or more subtasks with a certain probability; or having reached a critical point, he may find it desirable to select one of several alternate action pathways. Such a branching in the sequence may also be imposed by external conditions; the operator then takes one of several paths depending on these conditions. Such a subtask has the effect of causing the computer to select the next subtask (i.e., branch) without "consuming operator time." (No operator time is consumed in the model for decision subtasks since the time to shift attention between subtasks is included in the time for each subtask).

Decision subtasks may be appropriately placed anywhere in the sequence of subtasks. In this case, the values of $\bar{t}_{ij}$, $\bar{\sigma}_{ij}$, and essentiality have no meaning. The t_{ij} calculation is bypassed and the last pseudo-random number, R_3, from the previous subtask is compared against the p_{ij} of the decision subtask. Therefore, the next subtask to be performed as a result of the decision, is the one normally performed next in the event of success $(i, j)_s$ with probability $\bar{p}_{ij}$. The subtask indicated to be performed in the event of failure $(i, j)_f$ is executed with probability $1 - \bar{p}_{ij}$. Thus, both branching, skipping and looping are made possible. Schematic examples of the use of this technique are shown for a single operator in Figure 4, where solid arrows indicate paths for success and dotted arrows indicate paths in the event of subtask failure (with respective probabilities indicated). Boxes indicate action subtasks, and the symbol # indicates a decision subtask.

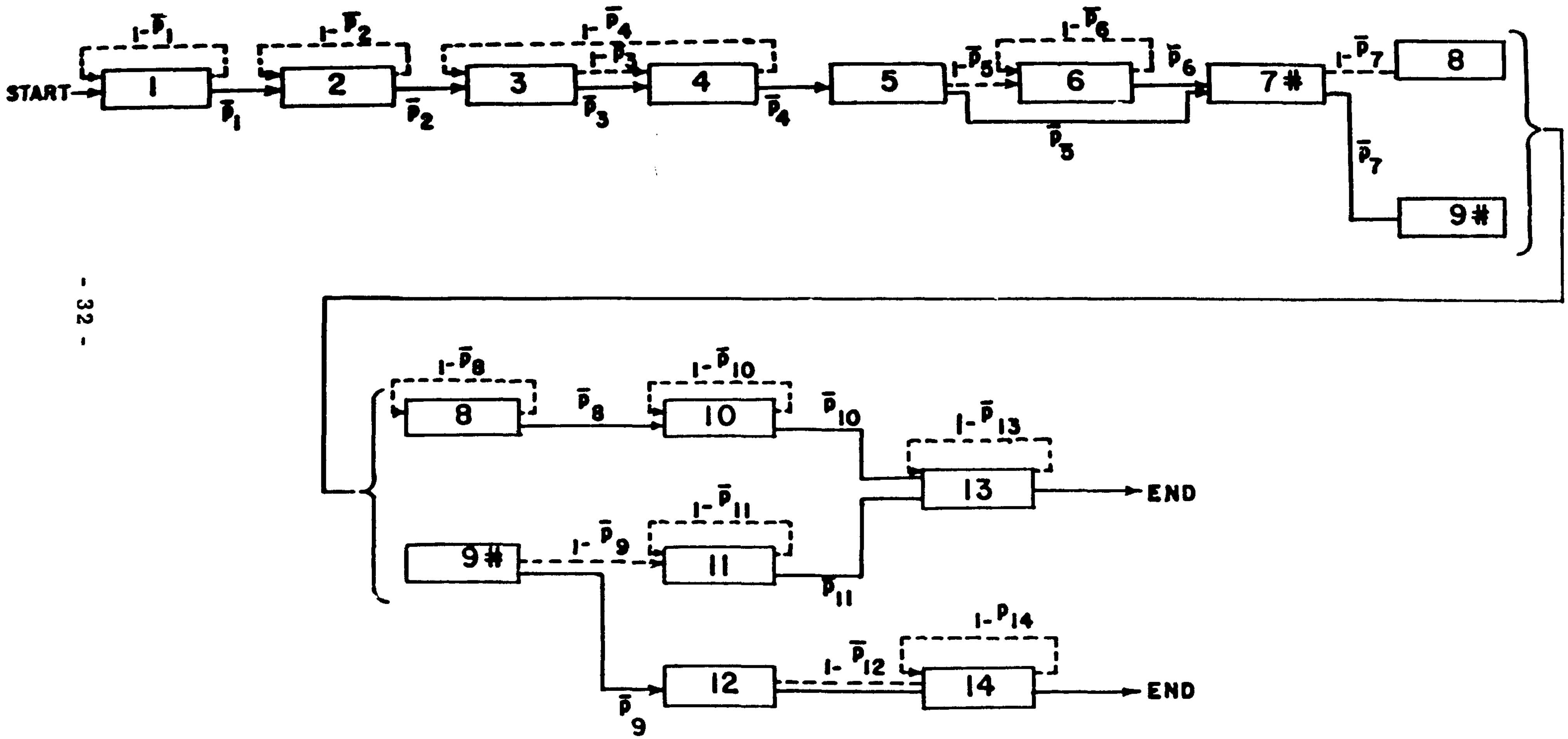


Figure 4 Schematic examples of progress between subtasks

Other Computer Operations

The remainder of the computer operations (starting at the circled i in Figure 1) are concerned with bookkeeping, updating memory values, and recording of results. In general, the model is organized so that at the completion of calculations for one run, any combination of the following three sets of recorded results may be produced:

(1) Detailed results	-	pertaining to individual subtasks
(2) Pseudo-random numbers	-	pertaining to individual subtasks
(3) Intermediate results	-	summary for one (out of N) simulations or iterations
(4) Final results	-	summary for all N iterations of a run

An example of the results pertaining to each subtask (see circled q, Figure 1) is given in Table 2. Table 2 is a direct reproduction of data prepared by the high speed printing device from a magnetic tape record. The table shows detailed results from one iteration followed by the corresponding intermediate results (circled u, Figure 1). All times and stress values have two decimal places.

Table 3 shows the pseudo-random numbers, R_0, R_1, R_2, and R_3, associated with the simulation shown in Table 2, together with K_i and V values. Here, leading blanks in the pseudo-random numbers are zeros; V and K_i have two decimal places.

Table 4 shows an example of the results printed at the completion of each run.

Table 2

Example of Detailed and Intermediate Results

Run	Trial	Iteration	Computer Switches
010	02	011	913 ON

i	j	s_{i1}	S_{i1}	t_{i1}	E_{i1}	Prob. Term	$\bar{P}_{i1}$	T^U_{i1}	Waiting Time	Note 1	Note 2	C_{i1}
01	1	0100	0100	000170	N	314	980	000361	000191	W	S	0000
02	1	0100	0100	000180	N	892	970	000541	000000	W	S	0000
03	1	0100	0100	000844	E	511	980	001385	000000	W	S	0000
04	1	0100	0100	000194	E	466	830	001579	000000	N	S	0000
05	1	0100	0100	000254	N	197	970	001833	000000	N	S	0000
06	1	0100	0100	000075	E	434	970	001908	000000	N	S	0000
07	1	0100	0100	000102	E	481	990	002010	000000	N	S	0000
08	1	0100	0100	000102	N	326	990	002112	000000	N	S	0000
09	1	0100	0100	000152	E	357	980	002264	000000	N	S	0000
10	1	0100	0100	000173	N	535	980	002437	000000	N	S	0000
11	1	0100	0100	000344	E	200	970	002781	000000	N	S	0000
12	1	0100	0100	000574	N	281	990	003355	000000	N	S	0000
13	1	0100	0100	000192	N	108	800	003547	000000	N	S	0000

i	j	s_{i2}	S_{i2}	t_{i2}	E_{i2}	Prob. Term	$\bar{P}_{i2}$	T^U_{i2}	Waiting Time	Note 1	Note 2	C_{i2}
01	2	0100	0100	000191	E	911	980	000191	000000	W	S	0000
02	2	0100	0100	000649	E	769	980	002034	001194	N	S	0000
03	2	0100	0100	000468	N	976	970	002502	000000	N	F	0000
03	2	0100	0100	000272	N	299	970	002774	000000	N	S	0000
04	2	0100	0100	000179	N	744	970	002953	000000	N	S	0000
05	2	0100	0100	000075	E	313	990	003028	000000	N	S	0000
06	2	0100	0100	000424	E	556	440	003452	000000	N	F	0000
06	2	0100	0100	000279	E	488	440	003731	000000	N	F	0000
06	2	0100	0100	000408	E	247	440	004139	000000	N	S	0000
07	2	0100	0100	000385	E	120	960	004524	000000	N	S	0000
08	2	0100	0100	000388	E	852	660	004912	000000	N	F	0000
08	2	0100	0100	000423	E	760	660	005335	000000	N	F	0000
08	2	0118	0118	000343	E	637	660	005678	000000	N	S	0014
09	2	0120	0120	000150	N	637	950	005828	000000	N	I	0014
10	2	0100	0120	000000	N	556	800	005828	000000	N	S	0014
20	2	0111	0111	000311	E	262	900	006139	000000	N	S	0009
21	2	0116	0116	000249	E	516	900	006388	000000	N	S	0013
22	2	0114	0114	000362	E	123	580	006750	000000	N	S	0011
26	2	0128	0128	000150	N	123	950	006900	000000	N	I	0011
27	2	0170	0170	000204	E	391	970	•007104	000000	N	S	0056

Run	Trial	Iteration	Initial R_0	Task Success or Failure
010	02	011	8738415 49	F

j	T_j	C_{ij} High	C_{ij} Low	C_{ij} Final	M_j	F_j	Stress Final	Stress Peak	i Peak S_{ij}	i Final	Time Remaining	Total Idle Time	Total Waiting Time
1	004160	000C	0000	0000	0150	1000	0100	0100	01	13	000613	000000	000191
2	007000	0056	0000	0056	0150	1000	0170	0170	27	26	•007104	000000	001194

Note 1:

W = Wait
N = No Wait

Note 2:

S = Success
F = Failure
I = Ignore

Table 3

Example of Pseudo-Random Number Results

R0	873841549	R1	370146647	R2	257513941	R3	911951823	K1	64-	V	191
R0	911951823	R1	254085469	R2	616946407	R3	314909221	K1	54	V	170
R0	314909221	R1	36937663	R2	487442989	R3	892218967	K1	100-	V	180
R0	892218967	R1	866326901	R2	867990703	R3	511002109	K1	39-	V	844
R0	511002109	R1	554096327	R2	625558981	R3	466486943	K1	111	V	194
R0	466486943	R1	268890829	R2	714962487	R3	769757461	K1	51	V	649
R0	769757461	R1	883882383	R2	475477149	R3	197921447	K1	59-	V	254
R0	197921447	R1	808234341	R2	768113023	R3	434569069	K1	94-	V	39
R0	434569069	R1	994397207	R2	955261621	R3	481994863	K1	11-	V	102
R0	481994863	R1	394614589	R2	329733767	R3	326871301	K1	10-	V	102
R0	326871301	R1	693623903	R2	319901709	R3	976795127	K1	34	V	468
R0	976795127	R1	881655381	R2	198776143	R3	357758429	K1	63	V	152
R0	357758429	R1	657565287	R2	625565861	R3	535307583	K1	105	V	173
R0	535307583	R1	681752749	R2	572748247	R3	200714741	K1	9-	V	344
R0	200714741	R1	749554223	R2	790892669	R3	299368007	K1	64-	V	272
R0	299368007	R1	578174021	R2	474732063	R3	744826189	K1	1-	V	179
R0	744826189	R1	496368567	R2	174775701	R3	281337103	K1	27-	V	574
R0	281337103	R1	215041309	R2	58213927	R3	313911781	K1	169-	V	35
R0	313911781	R1	59545343	R2	632066029	R3	556488087	K1	92	V	424
R0	556488087	R1	550334261	R2	993612783	R3	108668349	K1	108	V	192
R0	108668349	R1	9495047	R2	978955141	R3	488275423	K1	210-	V	279
R0	488275423	R1	219056269	R2	219858807	R3	247646421	K1	58	V	408
R0	247646421	R1	207149263	R2	114077789	R3	120123367	K1	178	V	385
R0	120123367	R1	594040101	R2	183130303	R3	852420909	K1	17	V	388
R0	852420909	R1	766352727	R2	826328181	R3	760794543	K1	90	V	423
R0	760794543	R1	227813629	R2	819730887	R3	768062661	K1	52	V	405
R0	556161847	R1	286955541	R2	416276623	R3	15059869	K1	45	V	345
R0	15059869	R1	643869607	R2	627678821	R3	671246463	K1	22-	V	289
R0	671246463	R1	478369389	R2	128998167	R3	368664501	K1	68	V	413
R0	368664501	R1	751003503	R2	288040509	R3	269211527	K1	85	V	163

Table 4

Summary (Run Results)

Run	Trial	N	Initial R_0	Note	Number of Successes	Number of Failures	Average Idle Time	Average Waiting Time	Average Terminal Stress	Average Terminal Cohesiveness	Average Peak Stress	Average Time Remaining
010	02	100	154904189	00296	071	029						
	j	1		F_j 1000	M_j 0150		000000	000275	0104	0002	0111	000050
		2		1000	0150		000000	001427	0203	0082	0203	000651

i	Last Subtask Completed j=1	Last Subtask Completed j=2	Number of Subtasks Failed j=1	Number of Subtasks Failed j=2	Number of Subtasks Ignored j=1	Number of Subtasks Ignored j=2
01	00000	00000	00001	00001	00000	00000
02	00000	00000	00000	00001	00001	00000
03	00000	00000	00003	00003	00000	00000
04	00000	00000	00022	00002	00000	00000
05	00000	00001	00004	00002	00016	00000
06	00000	00000	00005	00096	00000	00000
07	00000	00000	00000	00003	00000	00000
08	00000	00000	00000	00053	00013	00000
09	00000	00003	00003	00004	00000	00011
10	00001	00000	00002	00019	00018	00000
11	00001	00001	00004	00002	00000	00000
12	00006	00006	00000	00003	00029	00000
13	00092	00000	00020	00008	00006	00000
14	00000	00000	00000	00003	00000	00000
15	00000	00000	00000	00000	00000	00000
16	00000	00000	00000	00000	00000	00000
17	00000	00000	00000	00000	00000	00000
18	00000	00009	00000	00000	00000	00000
19	00000	00000	00000	00000	00000	00000
20	00000	00000	00000	00012	00000	00000
21	00000	00010	00000	00006	00000	00000
22	00000	00001	00000	00032	00000	00000
23	00000	00000	00000	00017	00000	00000
24	00000	00000	00000	00008	00000	00000
25	00000	00001	00000	00002	00000	00000
26	00000	00006	00000	00004	00000	00008
27	00000	00062	00000	00001	00000	00000

Note

Average of the N smaller times remaining

The flexibility in print formats is controlled by the two-position switches on the computer, as shown in Table 5.

Table 5

Console Switch Functions

Switch	Function
911	print all subtask data in the event of a subtask failure
912	print all subtask data for only the first of N iterations
913	print all subtask data
916	print R_0, R_1, R_2, R_3, K_i, V

Intermediate (iteration) summary results and final (run) summary results are always printed, regardless of switch settings.

Task Success

Task success occurs when the operators complete the required sequence of subtasks within the allotted time. Since each operator has an individual time limit on his performance and a task failure occurs only when the larger of these limits is exceeded, it is possible for the simulation to continue with one operator (arbitrarily selected as operator 1) having exceeded his limit. Should this be the case, the stress condition of this operator is set equal to his threshold value, M_j, for the duration of the task simulation.

Calculation of Pseudo-Random Numbers

The use of the model requires the sequential generation of pseudo-random numbers, uniformly distributed in the unit interval 0-1. The method selected for generation of these numbers is the power residue method

described by IBM (1959). This general method as applied to the model 705 computer may be summarized as follows:

1. select any starting value of 9 digits, R_0
2. form the product 10003 R_0
3. the least significant 9 digits of the product is R_1
4. each successive pseudo-random number, R_{m+1}, is obtained from the 9 low order digits of the product 10003 R_m

By this method, a given pseudo-random number is dependent upon the preceding one and the process is acceptable only since the quantity of numbers generated by the computer before repetition is large. The method produces approximately 50,000,000 nine digit pseudo-random numbers before repetition. Employment of this method permits the exact repetition of any simulated task or subtask if the initial random number for that task or subtask is known. The exact repetition of a random process is thus facilitated by the recording of initial R_0 values for each iteration and enables detailed review of any selected simulated task.

During the calculations, three pseudo-random numbers are required for each simulated subtask. Since, for the in-flight refueling maneuver here reported, there are 13 subtasks for the first operator and 27 for the second (assuming completion of each task with no subtask repetitions), 40·3 or 120 pseudo-random numbers were required for each iteration. Since each of the 44 computer runs included 100 iterations, then only 528,000 (100·120·44 = 528,000) pseudo-random numbers were generated during the course of the calculations.

Calculation of Random Deviates

In the calculation of t_{ij}, it is necessary to generate values of a random variable with a frequency function equivalent to that of the normal distribution (i.e., a random deviate). This was done by the direct method discussed by Box and Muller (1958) and by Muller (1959). This method gives higher accuracy than previous methods and also compares favorably with other methods in computation speed. The technique is based on the availability of two random numbers in the unit interval, R_m and R_{m+1}, taken from the same rectangular density function (see preceding section). Then X_1 and X_2

$$X_1 = (-2\ln R_m)^{\frac{1}{2}} \cos 2\pi R_{m+1}$$

$$X_2 = (-2\ln R_m)^{\frac{1}{2}} \sin 2\pi R_{m+1}$$

are a pair of independent random variables from the same normal distribution with a mean of zero and unit variance. This method is reported to produce normal deviates with a precision of approximately 5×10^{-7} except for probabilities less than 4×10^{-8}.

Assumptions

It is assumed in the use of the model that the operators remember and execute the correct sequence of subtasks. It should be noted, however, that the possibility of one or both operators neglecting a subtask or of rearranging the performance of a sequence of subtasks may be studied by additional runs using these different sequences, i.e., assuming new subtasks or subtask sequences.

Similarly, a change in the predetermined sequence of subtasks by either or both operators is conceivable in the event of emergency. Such a dangerous situation may result from operator action or an external event during the task. In either case, it may be assumed that the operators, upon noticing the danger, will abandon their normal tasks and take up the emergency sequence of subtasks associated with the problem of survival, and the sequence of operations will change. Thus, the simulation of dangerous conditions need not be especially provided for as an integral part of the model since the danger condition may itself be studied using the model. This is done by establishing special danger sequences to be simulated. Therefore, this situation does not limit the model.

It must also be assumed that $\overline{p}_{ij}$, $\overline{t}_{ij}$, and $\overline{\sigma}_{ij}$ are independent of whether the subtask is being performed for the first time or is being repeated due to a previous subtask failure. However, it is noted that upon repetition, less time will remain for the operator, possibly affecting the stress and consequently affecting p_{ij}, t_{ij}, and σ_{ij}.

CHAPTER III

THE IN-FLIGHT REFUELING TASK

Task Description

The first task selected for simulation using the two-man model described in Chapter II is maneuvering two in-flight aircraft into the position required prior to the transfer of fuel from one to another. The first operator, $j = 1$, is selected to be the pilot of the tanker aircraft and the second operator, $j = 2$, is the pilot of the ship to be refueled (strike aircraft). The objective is the mid-air insertion by the second operator of a probe into a drogue extended by the pilot of the tanker aircraft. The actual passing of fuel, a largely mechanical action, is not simulated. The airplanes involved in the present series of flights were an F8U receiver and an A4D-2N tanker. The probe through which the fuel is passed is of the "cobra" type (retractable). It is mounted at the side of the cockpit of the F8U and extends forward at about the pilot's shoulder level. In all cases, the aircraft were flying abreast at the start of the run and the probe of the strike aircraft was extended prior to initiation of the run. In order to derive the sequence of subtasks involved, together with the relevant auxiliary data, four experienced pilots were first asked to list the subtasks involved. These four separate analyses were then synthesized into a composite best estimate and resubmitted to the pilots for review. Following this review, the analysis was revised in accordance with their suggestions and criticisms and resubmitted for further review. At this point, the pilots unanimously agreed on the outlined procedures, and the resultant sequence of subtasks was adopted.

Figure 5 is a presentation against a timeline of the subtask sequence for both operators. Such a formulation has been found very useful in organizing subtask data for the model. In this figure, the time relationships of performance of the two operators are shown schematically, using average execution times, and assuming no subtask failures. Average waiting times, operator time limit values, (T_j), and decision probabilities are also included.

Tables 6 and 7 present the complete task analysis for operators 1 and 2 respectively.

At the start of the task, the tanker and the strike aircraft are assumed to be flying abreast of each other at a rate greater than that optimal for in-flight refueling. For the purposes of the present simulation, it is further assumed that the pilot of the tanker aircraft is aware that refueling is to take place, but has not prepared for the task by reducing airspeed or by other actions.

Initiation of the task takes place when the pilot of the strike aircraft reports "Ready to refuel" ($i = 1$, $j = 2$). At the time of this report the tanker and the strike aircraft are abreast of each other. The tanker pilot acknowledges by reporting "Ready" to extend drogue ($i = 1$, $j = 1$), and reduces airspeed. It may be assumed that the strike aircraft reduces power at the same time as the tanker but that an additional reduction is necessary to bring the strike somewhat behind the tanker after the latter has attained a speed optimal for the task. The execution of this action by the strike aircraft ($i = 2$, Table 7) is dependent on the tanker's attainment of a stable speed (i.e., the tanker pilot's completion of his third subtask), and hence this subtask has a non-zero d_{ij} value for the strike aircraft.

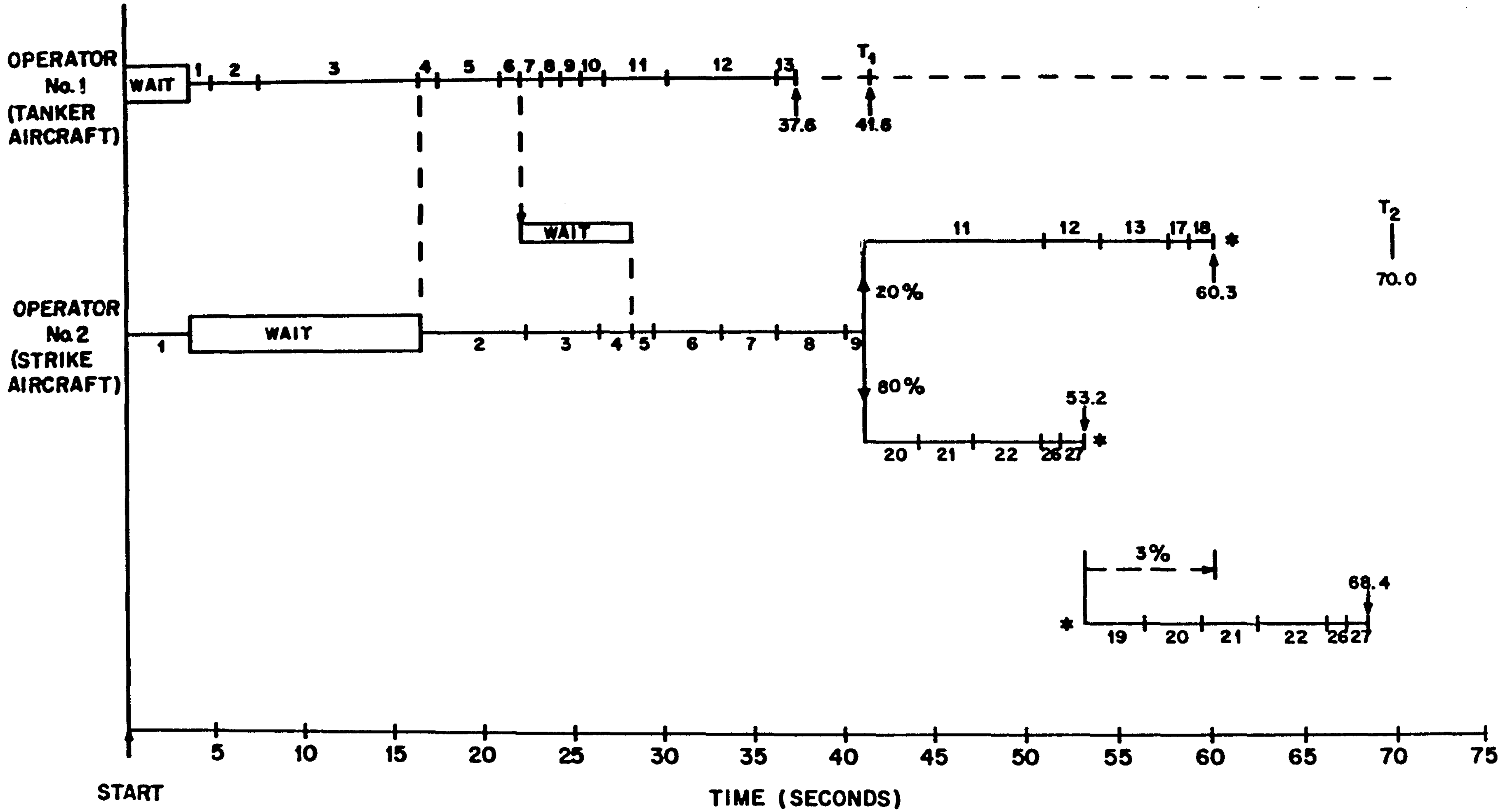


Figure 5 Schematic time diagram of the in-flight refueling subtasks

Table 6

Task Analysis Data for In-Flight Refueling--Tanker

Subtask No. i	Subtask	$\bar{t}_{ij}$	$\bar{\sigma}_{ij}$	$\bar{p}_{ij}$	d_{ij}	E_{ij}	I_{ij}	$(i,j)_f$	$(i,j)_s$	Communi-cations	T^E_{ij}	T^N_{ij}	Control Number	Action Type
1	Report "ready" to extend drogue	1.3	0.74	0.98	1	0	0	1	2	1	27.6	7.4	1	Communication
2	Check instruments: heading, airspeed, altitude, power setting, gyro	3.6	1.80	0.97	1	0	0	2	3	0	26.1	7.6	-	Monitor
3	Adjust power	9.0	1.44	0.98	1	1	0	3	4	0	24.6	5.5	3	Lever
4	Trim	1.1	0.76	0.83	1	1	0	4	5	0	15.6	5.5	2	Thumbwheel
5	Check same instruments as above	3.6	1.80	0.97	1	0	0	5	6	0	14.5	5.5	-	Observation
6	Move "Retract-Extend" switch to "Extend"	1.1	0.76	0.99	1	1	0	6	7	0	13.0	3.4	1	Toggle
7	Move "Dump On-Off" switch to "Off" position	1.1	0.76	0.99	1	1	0	7	8	0	11.9	3.4	1	Toggle
8	Move "Dim-Bright" light switch to appropriate setting	1.1	0.76	0.99	1	0	0	8	9	0	10.8	3.4	1	Toggle
9	Check fuel transfer counter for zero-gal. setting	1.2	0.50	0.98	1	1	0	9	10	0	9.3	3.8	-	Observation
10	Check on extension of drogue	1.2	0.50	0.98	1	0	0	10	11	0	8.1	3.8	-	Observation
11	Check same instruments as before	3.6	1.80	0.97	1	1	0	11	12	0	6.6	4.1	-	Observation
12	Adjust power (to compensate for added drag of drogue)	6.0	0.96	0.99	1	0	0	12	13	0	3.0	4.1	2	Lever
13	Trim	1.1	0.76	0.80	1	0	0	13	END	0	1.5	-0.4	2	Thumbwheel

Table 7

Task Analysis Data for In-Flight Refueling--Strike

Subtask No. i	Subtask	$\bar{t}_{ij}$	$\bar{\sigma}_{ij}$	$\bar{p}_{ij}$	d_{ij}	E_{ij}	I_{ij}	$(i.j)_f$	$(i.j)_f$	Communi-cations	T^E_{ij}	T^N_{ij}	Control Number	Action Type
1	Report "Ready to refuel".	2.6	1.08	0.98	0	1	0	1	2	1	53.2	2.0	3	Communication
2	Adjust power	6.0	0.96	0.98	3	1	0	2	3	0	36.7	2.0	2	Lever
3	Evaluate relative position of tanker	4.0	2.00	0.97	3	0	0	3	4	0	30.7	2.0	-	Evaluation
4	Check airspeed, power setting	1.8	0.50	0.97	3	0	0	4	5	0	29.2	-0.5	-	Monitor
5	Check that drogue has extended	1.2	0.50	0.99	6	1	0	5	6	0	27.7	-0.8	-	Monitor
6	Move astern of tanker	3.8	0.48	0.44	6	1	0	6	7	0	26.5	-0.8	6	Joystick
7	Adjust power	3.0	0.48	0.96	6	1	0	7	8	0	22.7	-0.8	1	Lever
8	Adjust heading and altitude	3.8	0.48	0.66	6	1	0	8	9	0	19.7	-0.8	3	Joystick
9	Trim	1.1	0.76	0.95	6	0	0	9	10	0	15.9	-0.8	1	Thumbwheel
10	"Decision subtask"	0.0	0.00	0.80	6	0	-0	11	20	0	0.0	0.0	-	Decision
11	Observe steadiness of drogue	10.0	3.00	0.90	6	1	0	11	12	0	20.0	-0.4	-	Observation
12	Adjust closure rate	3.0	0.48	0.90	6	1	0	12	13	0	10.0	-0.4	1	Lever
13	Adjust heading and altitude	3.8	0.48	0.58	6	1	0	14	17	0	7.0	-0.4	1	Joystick
14	Adjust heading and altitude	3.8	0.48	0.58	6	1	0	15	17	0	7.0	-0.4	1	Joystick
15	Adjust heading and altitude	3.8	0.48	0.58	6	1	0	16	17	0	7.0	-0.4	1	Joystick
16	Adjust heading and altitude	3.8	0.48	0.58	6	1	0	19	17	0	7.0	-0.4	1	Joystick
17	Trim	1.1	0.76	0.95	6	0	0	17	18	0	3.2	-0.4	1	Thumbwheel
18	Observe insertion of probe in drogue	1.2	0.50	0.97	6	1	0	19	END	0	1.7	0.0	-	Observation
19	Adjust power	3.0	0.48	0.98	6	1	0	19	20	0	16.0	-0.4	1	Lever
20	Observe steadiness of drogue	3.0	1.00	0.90	6	1	0	20	21	0	13.0	-0.4	-	Observation
21	Adjust closure rate	3.0	0.48	0.90	6	1	0	21	22	0	10.0	-0.4	1	Lever
22	Adjust heading and altitude	3.8	0.48	0.58	6	1	0	23	26	0	7.0	-0.4	1	Joystick
23	Adjust heading and altitude	3.8	0.48	0.58	6	1	0	24	26	0	7.0	-0.4	1	Joystick
24	Adjust heading and altitude	3.8	0.48	0.58	6	1	0	25	26	0	7.0	-0.4	1	Joystick
25	Adjust heading and altitude	3.8	0.48	0.58	6	1	0	19	26	0	7.0	-0.4	1	Joystick
26	Trim	1.1	0.76	0.95	6	0	0	26	27	0	3.2	-0.4	1	Thumbwheel
27	Observe insertion of probe in drogue	1.2	0.50	0.97	6	1	0	19	END	0	1.7	0.0	-	Observation

A d_{ij} change is again shown for the strike aircraft at subtask 5 because the strike pilot cannot observe the fully extended drogue until the tanker pilot has completed his subtask 6, i.e., has actually extended the drogue. Upon seeing the extended drogue, the strike pilot moves his aircraft astern of the tanker.

After the period of observation of the motion of the drogue ($j = 2$, $i = 11, 20$), the strike pilot closes in for engagement. If failure occurs on the first three of four attempts to adjust heading and attitude correctly ($i = 13$-16 or 22-25), it is assumed that the failed subtask is simply repeated. If the fourth attempt is failed, however, it is assumed that the strike pilot reduces power ($i = 19$), again observes the motion of the drogue ($i = 20$) for a short time, and again proceeds to close in.

Subtask 10 is a "decision subtask" for the strike pilot and branching occurs. This subtask was inserted to cause a decision by the computer. Eighty per cent of the time the computer considers subtask 20 next. Twenty per cent of the time the computer considers subtask 11 next (see Figure 5). The purpose of this branching is to provide for two different amounts of time being spent on "observing steadiness of drogue" ($i = 11, 20$). This allows differential observation time as might be required in accordance with varying air turbulence. With the exception of this difference between the initial subtasks of the two branches, the subtasks of both branches are identical. It should be noted, however, that if, on the first time through the task, the decision is made to follow the branch headed by subtask 11

and if, on the last subtask of that branch (i = 18), a probe insertion failure occurs, the computer takes the second (i = 20) branch on the next attempt. It is assumed in this case that the previous observations of drogue motion will be recalled and applied. Upon failure to execute the last subtask of the subtask 20 branch, that same branch is followed again until success is finally achieved.

Further activity of the tanker pilot is relatively straightforward. His first subtask, that of acknowledging the strike pilot's report, is accomplished only after completion of that activity by the strike, and hence $d_{11} = 1$. Subsequent activity of the tanker can occur at any time after the completion of subtask 1. This activity involves the reduction of power until the optimal speed for the task is attained, the performance of the proper sequence of actions for permitting fuel transfer, and in general keeping his aircraft flying steadily.

Subtask Data

The values of $\bar{t}_{ij}$ and $\bar{\sigma}_{ij}$ for each subtask of the total in-flight refueling task are given in Tables 6 and 7. With the exception of the values for thumb wheel setting (trim) and communication, every $\bar{t}_{ij}$ and $\bar{\sigma}_{ij}$ is the same as that employed in previous applications for the Applied Psychological Services' one-man model. The method by which these values were derived has been described previously (Siegel and Wolf, 1959a; 1959b). Briefly, the $\bar{t}_{ij}$ and $\bar{\sigma}_{ij}$ data for individual subtasks were derived by doubling such values obtained from a literature review of representative laboratory

experiments and by adding a constant (0.6 seconds to $\overline{t}_{ij}$; 0.4 seconds to $\overline{\sigma}_{ij}$) to account for the time required for shift of attention from one discrete response to another.

Consider the two $\overline{t}_{ij}$'s and $\overline{\sigma}_{ij}$'s which were not previously employed. For the thumb wheel adjustment (trim), the same $\overline{t}_{ij}$ and the same $\overline{\sigma}_{ij}$ were used as those calculated on the basis of the experimental literature for setting a toggle switch ($\overline{t}_{ij} = 1.1$; $\overline{\sigma}_{ij} = 0.76$). This procedure was felt to be reasonable since, in the case of the trim action, the time required to move a thumbwheel should approximate the time required to throw a switch.

With respect to the $\overline{t}_{ij}$ and $\overline{\sigma}_{ij}$ values for communication subtasks, the basic time required per word was taken to be 0.67 seconds. This estimation is based on the data of Miller (1951), who reported the average speaking rate to be 1.5 words per second. Adding the constant 0.6 results in an approximate value of 1.3 seconds for one word, or 0.66 N + 0.6 seconds for N words. The $\overline{\sigma}_{ij}$ value for verbal report was arbitrarily selected to be 0.34 seconds per word plus the constant 0.4 seconds. A summary of all $\overline{t}_{ij}$ and $\overline{\sigma}_{ij}$ data for basic control actions is given in Table 8.

Table 8

Summary of Average Execution Times and Average Standard Deviations for Basic Operator-Control Actions

	Average Execution Time $\bar{t}_{ij}$ (seconds)	Average Standard Deviation $\bar{\sigma}_{ij}$ (seconds)
Set Toggle Switch	1.1	0.76
Set Rotary Control	8.6	3.00
Push Button	4.2	1.02
Lever (throttle) Setting	3.0	0.48
Joystick Setting	3.8	0.48
Read Instrument, N Instruments	0.6N + 0.6	0.2N + 0.2
Trim	1.1	0.76
Communication, N Words	0.66N + 0.6	0.34N + 0.4
Minimum Value	0.75	-

Very low success probabilities are associated with certain of the subtasks (e.g., joystick and trim settings). In these multiple action subtasks, several trials of the same action are usually required in order to gain a given probability of success, but a single successful action at any time may be sufficient for subtask success. Hence, these subtasks were organized for the computer as subtasks requiring a single control action with a relatively low success probability. The actual determination of a probability of success on any single trial was made as follows:

> If p is the probability of success on a single trial and p* is the probability of at least one success after n trials, then
>
> $$p = 1 - \sqrt[n]{1 - p^*}$$

The d_{ij}, E_{ij}, I_{ij}, $(i,j)_f$ and $(i,j)_s$ data were determined from the basic task analysis. The T_{ij}^E and T_{ij}^N data were obtained from $\bar{t}_{ij}$ and E_{ij} data. An example will serve to demonstrate the method of calculating T_{ij}^E and T_{ij}^N data. Consider T_{12}^E, i.e., the average time required by the second operator to complete his task starting at the beginning of subtask 1. This was calculated by a weighted addition of t_{ij} for essential values as shown in Table 9. In calculating T_{ij}^E, when a non-essential subtask execution time is less than 1.5 seconds (e.g., i = 26), 1.5 seconds was assumed.

Table 9

Calculation of T^E_{12}

i	Average time spent	Factor	Note	Totals
1	2.6			
wait for j = 2	13.9			
2	6.0			
3	1.5			
4	1.5	100%	Always	
5	1.2		performed	
6	3.8			
7	3.0			
8	3.8			
9	1.5			
Total x factor				38.8
11	10.0			
12	3.0		Performed	
13	3.8	20%	20% of the	
17	1.5		time, see	
18	1.2		Figure 5	
Total x factor				3.9
20	3.0			
21	3.0			
22	3.8	80%	See Figure 5	
26	1.5			
27	1.2			
Total x factor				10.0
			Alternate path	
19	3.0		performed 3%	
20 - 27	12.5	3%	of time, see	
Total x factor			Figure 5	0.5
Grand Total			T^E_{12} =	53.2

T_1 and T_2 Values Employed

The values of T_1 and T_2 were determined on the basis of estimated proficiency of highly experienced pilots. These estimates were normalized to an expectancy for the average pilot.

Outside Criteria

In order to determine the degree to which the results obtained by the model agree with reality, data were collected which indicate the degree of in-flight refueling success achieved by pilots of known capability. These data are given in Table 10 as the number of "hits" (successes) and "misses" (failures) out of a total of 16 flights. A "hit" is defined as the successful engagement of the probe on the first attempt. Since 10 of the 16 flights resulted in "hits," the probability of task success associated with these pilots is calculated as 0.625.

Table 10

Outside Criterion Data for In-Flight Refueling Maneuver

Run	Altitude (Feet)	Indicated Air Speed (Knots)	Hits	Misses
1	20,000	250	1	-
2	20,000	250	1	-
3	20,000	250	-	1
4	20,000	250	-	1
5	25,000	245	1	-
6	25,000	245	1	-
7	25,000	260	1	-
8	25,000	260	-	1
9	31,500	240	1	-
10	31,500	250	-	1
11	31,500	260	-	1
12	31,500	260	1	-
13	35,000	255	-	1
14	35,000	255	1	-
15	35,000	255	1	-
16	35,000	255	1	-
Total			10	6

Computations Performed

Forty-four computer runs were made, each consisting of 100 simulations*. This value for the initial condition, N, was selected as a compromise between reasonable computational time and stability of resultant data. Each run consumed approximately five minutes and twenty seconds of computational time, exclusive of the time required on auxiliary equipment used in listing the results.

The actual calculations performed were accomplished over several periods of computer operation. After each group of runs was completed, the results were reviewed to determine the parameters to use in the next calculations. The parameter values used for the 44 runs are shown in Table 11. The location of the decimal point indicating the range of permissible values in the pertinent variables used in the calculations is given in Table 12.

* In addition, a large number of unreported runs were made to assemble, verify, and reassemble the computer program.

Table 11

Initial Conditions and Parameters for the In-Flight Refueling Task Simulation

T_1 = 41.6 seconds N = 100 iterations
T_2 = 70.0 seconds R_0 = 123456789

Run	M_1	M_2	F_1	F_2
1	1.25	1.5	1.0	1.0
2	1.5	1.25	1.0	1.0
3	1.5	1.5	1.0	1.0
4	1.5	3.0	1.0	1.0
5	1.5	4.0	1.0	1.0
6	3.0	1.5	1.0	1.0
7	3.0	3.0	1.0	1.0
8	3.0	4.0	1.0	1.0
9	4.0	1.5	1.0	1.0
10	4.0	3.0	1.0	1.0
11	4.0	4.0	1.0	1.0
12	1.25	1.5	0.9	0.9
13	1.5	1.25	0.9	0.9
14	1.5	1.5	0.9	0.9
15	1.5	3.0	0.9	0.9
16	1.5	4.0	0.9	0.9
17	3.0	1.5	0.9	0.9
18	3.0	3.0	0.9	0.9
19	3.0	4.0	0.9	0.9
20	4.0	1.5	0.9	0.9
21	4.0	3.0	0.9	0.9
22	4.0	4.0	0.9	0.9
23	1.25	1.5	1.1	1.1
24	1.5	1.25	1.1	1.1
25	1.5	1.5	1.1	1.1
26	1.5	3.0	1.1	1.1
27	1.5	4.0	1.1	1.1
28	3.0	1.5	1.1	1.1
29	3.0	3.0	1.1	1.1
30	3.0	4.0	1.1	1.1
31	4.0	1.5	1.1	1.1
32	4.0	3.0	1.1	1.1
33	4.0	4.0	1.1	1.1
34	1.25	1.5	1.3	1.3
35	1.5	1.25	1.3	1.3
36	1.5	1.5	1.3	1.3
37	1.5	3.0	1.3	1.3
38	1.5	4.0	1.3	1.3
39	3.0	1.5	1.3	1.3
40	3.0	3.0	1.3	1.3
41	3.0	4.0	1.3	1.3
42	4.0	1.5	1.3	1.3
43	4.0	3.0	1.3	1.3
44	4.0	4.0	1.3	1.3

Table 12

Scaling of Selected Computer Data

Input

M_j	XX.XX
F_j	X.XXX
T_j, $\bar{t}_{ij}$, T^E_{ij}, T^N_{ij}, I_{ij}	XXXX.XX
N	XXX.
R_0, R_1, ...	XXXXXXXXX.
$\bar{\sigma}_{ij}$	XX.XX
$\bar{p}_{ij}$, p_{ij}	X.XXX
E_{ij}, communication indicator	X.
$(i,j)_s$, $(i,j)_f$, d_{ij}	XX.

Output

s_{ij}, S_{ij}, C_{ij}, A_{ij}	XX.XX
t_{ij}, T^U_{ij}, waiting time, idle time	XXXX.XX
V, K	X.XX

Confidence Limits

Each run of N = 100 simulations yielded results indicating the number of successes and failures from which a probability of success (or failure) was determined. Of course, greater confidence can be placed on this probability if a larger value for N is selected. This leads, then, to the question: what confidence can be placed on the specific values of success probability which result from each computer run? To answer this question, confidence limits may be calculated according to the method of standard error of percentages. As stated in McNemar, 1949:

> "...it often happens that the research worker can easily classify individuals only on the basis of presence or absence of a certain characteristic (success or failure of a task)...but not measured in a graduated manner. When individuals are classified into categories on the basis of some characteristic or attribute it is usually desirable to reduce the frequencies to percentages...the given percentage is based on a sample, presumably random, of a defined population and we are faced with the problem of making an inference from the sample value to the population value, i.e., from P to p*, where P stands for the observed percentage and p* stands for the percentage of the defined population, who show the characteristic ...the standard error of percentage will be given approximately by: $\sigma^2_{p*} = \frac{P(100-P)}{N}$.
>
> In the long run one would be correct 95% of the time in concluding that the population value lies within the limits $P \pm 1.96\ \sigma_{p*}$."

The 99% confidence limits are $P \pm 2.58\ \sigma_{p*}$; the .68% confidence limits are $P \pm \sigma_{p*}$. (It is not safe to use σ_{p*} for setting confidence limits for population values when extreme percentages are involved.)

Errors of largest magnitude are experienced at a probability of 0.5. For this particular case with N = 100, the one sigma confidence limits are 0.50 ± 0.05 and 95% confidence limits are 0.50 ± 0.098. For the case of success probabilities of 0.25 and N = 100, the 68% confidence limits are 0.25 ± 0.043 and the two sigma limits are 0.25 ± 0.085.

CHAPTER IV

THE COMPUTER AND THE PROGRAM

Description

The computational system employed by Applied Psychological Services in the present study is the model 705 Data Processing System manufactured by the International Business Machines Corporation. The facility, located at the U. S. Naval Aviation Supply Office, Philadelphia, was employed. The 705, a large scale high-speed system, is composed of an integrated set of record reading and writing devices interconnected through a central processing and control unit. Input to the system can be from magnetic tape or punched cards. Output is in the form of magnetic tape, punched cards, or printed reports. Data entered into the system or processed by the system may be letters of the alphabet, decimal numbers, or any of eleven punctuation marks or symbols. Detailed operating techniques and programming examples are given in the IBM references (1958, 1959). A summary of the pertinent features of the system is given in Table 13.

Table 13

Operating Characteristics of the IBM 705 Computing System

Type	Electronic, stored program, serial-parallel, coded decimal notation, self-checking	
Storage Capacity	40,000 characters, magnetic core	
	60,000 characters, magnetic drum	
Input-Output	16 magnetic tape units:	15,000 characters per second
	card readers:	250 cards per minute
	card punch:	100 cards per minute
	line printer:	120 characters per line, 150 lines per minute
Basic Arithmetic Times	Addition:	8400 5 digit nos. per second
	Multiply:	1250 (5 digits $\times$ 5 digits) per second
	Divide:	550 (6 digits $\div$ 4 digits) per second
	Logical decisions:	29400 per second

The Program

The work accomplished by the 705 in solving a problem or processing data consists of the high speed execution of many instructions. The entire set of instructions used in solving a problem forms a program for the computer. Instructions for a given procedure are stored in the memory of the machine. These instructions are referred to, one at a time, in the sequence required for handling each problem. Each instruction not only specifies the functional cperation to be performed, but also directs the operands and results into appropriate channels. Provision is possible in programming for alternative routines in which the "logical" features of the machine choose between two separate courses of action. In this case, the control operations are said to be conditional. By providing a stored program with the ability to control its own course of execution, these conditional operations immeasurably increase the scope of the system.

At the start of each procedure, the program of instructions is read into the memory from tape or cards and is stored for use with each operational subtask. This one entry of instructions suffices to set up all units. Each time an operation is performed, the 705 takes the instruction from its memory, decodes and executes the instruction and then refers to its memory for the next instruction.

The model as programmed will accommodate a task consisting of 100 subtasks, including decision subtasks, for each operator. Of the 40,000 memory locations available, 25,000 are used in the program. The precise distribution of memory location employment is:

Memory Location	Content
0 - 1,300	reading and writing routines
1,301 - 8,500	instructions
8,501 - 19,430	input and output records and working storage
19,431 - 22,005	floating point sub-routines (machine generated instructions)
22,006 - 25,000	constants

The program was written symbolically and assembled for computer operation using the Autocoder System. The IBM 705 Autocoder System (1957) makes available a greatly simplified technique for instructing the machine (i.e., it is an assembly program that automatically converts or assembles the programmer's symbolic instructions into actual computer instruction). Without any simplified programming techniques, a human programmer must write instructions in actual machine language. This procedure is difficult, time consuming, and subject to clerical error. Moreover, it requires a monumental effort to keep account of the proper address portion of the instructions. A program of as many as 3,000 instructions written in this manner is difficult to read or to analyze for corrections and additions.

The most distinguishing feature of the Autocoder System is its ability to handle "macro-instructions." A macro-instruction (special Autocoder instruction) permits one instruction to take the place of several 705 instructions. The Autocoder also systematically checks the instructions written by the programmer. Upon detection of errors, the programmer is notified by typed messages during the assembly process. In some cases, the Autocoder diagnoses the intention of the programmer and corrects the error.

CHAPTER V

RESULTS AND DISCUSSION

The fundamental research reason for applying a model such as that here described is to gain insight into its validity. If the validity of the model can be established, the model may then be used, in accordance with its objectives, for predictive purposes in proposed systems or in the early developmental stage of a system.

The validity of such a model may be considered from several points of view. First, the psychological concepts and their mathematical representations may be examined. To the extent that the user of the model accepts these concepts and their representations, to that extent will the model be acceptable to him. The psychological concepts and the method of their mathematical and digital representations have been presented in previous sections of this report.

A second approach to questioning the validity of such a model is to investigate how the results from the model agree with other reality experience. The comparison of the model with reality experience may be qualitative, i.e., the agreement of the model with common sense expectation, or it may be quantitative. Both approaches are taken in the current chapter. The results are presented and discussed with empirical and qualitative focus on each of the following topics:

1. the percentage of successful refuelings

2. success percentage as a function of stress threshold

3. comparison of these success data with outside criteria data

4. the amount of operator waiting and idle time during the simulated task

5. the amount of time remaining to each member of the simulated team after task completion

6. the peak stress of the operators during each simulated refueling and at the end of the simulation

7. the number of non-essential subtasks ignored by the operators

8. the team cohesiveness

9. the number of subtasks failed by each operator

Success Percentage as a Function of F_j

Success in the task is defined as the proper seating of the probe by the pilot of the strike aircraft into the drogue extended by the pilot of the tanker aircraft. This involves the successful completion of at least all essential subtasks and ends with subtask 13 for the tanker (Table 6) and either subtask 18 or 27 for the strike pilot (Table 7).

A summary of the primary results of the 44 runs is shown in Table 14. This table gives the total number of successful simulated refuelings in each run of 100 iterations. Since, in each case, N was selected to be 100, the data reported represent success percentage. The data in each cell are considered as representative of the value obtained for coordinates at the center of the cell for each of four pairs of F_j values: $F_1 = F_2 = 0.9$; $F_1 = F_2 = 1.0$; $F_1 = F_2 = 1.1$; $F_1 = F_2 = 1.3$.

Although the model provides for this possible condition, no attempt was made in this early study to consider teams in which F_1 does not equal F_2.

Table 14 suggests that the model indicates substantial differences in performance as simulated pilots deviate from average ($F_{12} = 1$). Faster pilots ($F < 1$) achieved greater success percentages than slower pilots ($F > 1$).

Table 14

Percentage of Successful Iterations for Each of Four F Values at Various M_1 and M_2 Values

M_2 \ M_1	1	1.5	2	3	4
1					
		86/74/40/10			
1.5	91/65/47/9	92/68/55/10		90/75/54/6	91/73/52/11
2					
3		90/81/56/14		89/74/46/9	89/79/51/9
4		92/81/49/16		94/79/49/14	90/77/53/10

Key:

$F_1 = F_2 =$
0.9/1.0/1.1/1.3

The mean over all 11 runs for each set of F_j values is given in Table 15.

Table 15

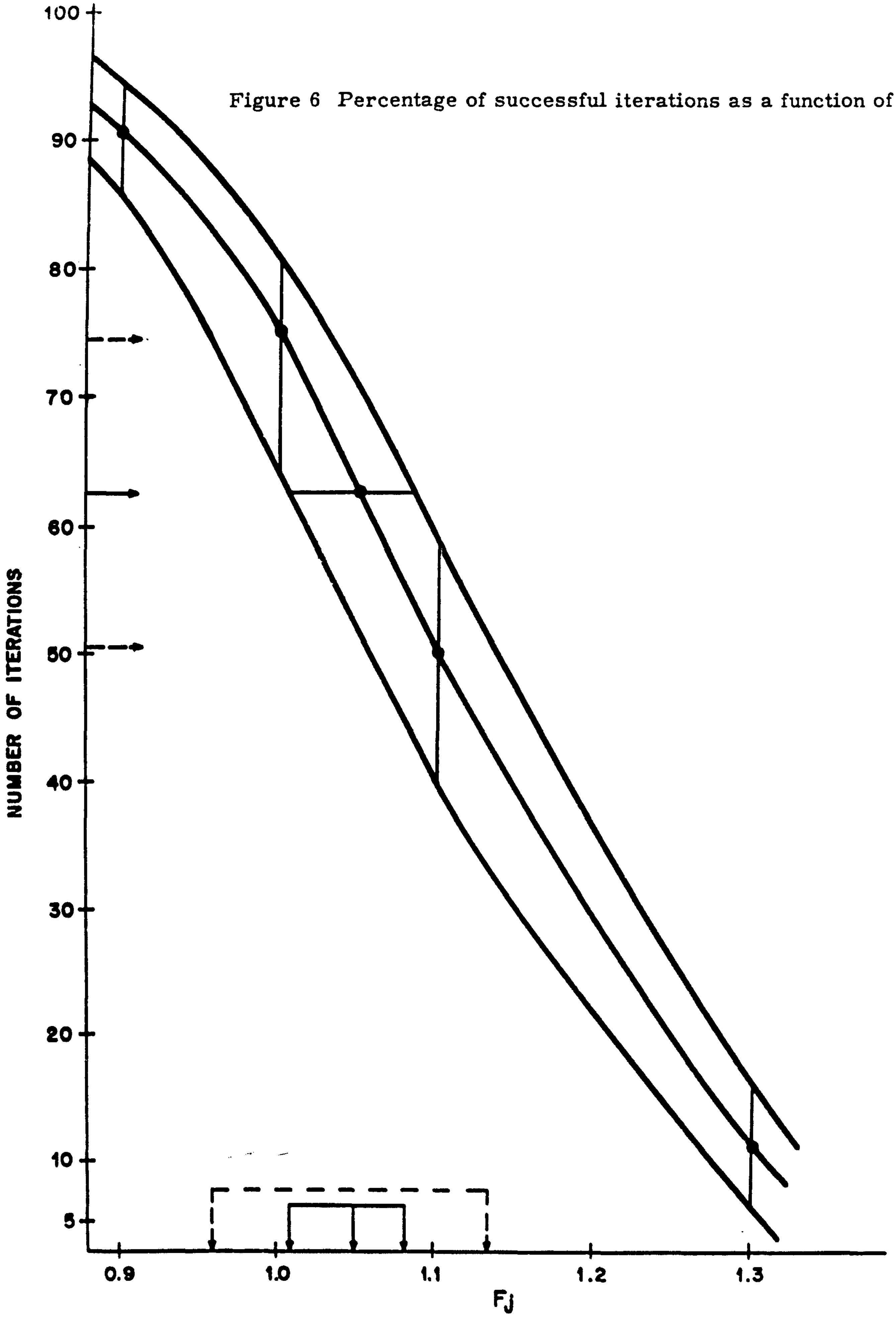
Mean Success Percentage for Various F_j Values

F_j	Mean Success Percentage	First Difference
0.9	90.4	-
1.0	75.1	15.3
1.1	50.2	24.9
1.3	10.7	39.5

The first difference in Table 15 indicates a 15.3 per cent decrease in success probability as a result of a 10 per cent decrease in the individuality factor (0.9 to 1.0). This effect is even more pronounced for slower operators.

This relationship is shown in Figure 6. Here, average success percentages over the 11 sets of runs are plotted for each of the four F_j values. Vertical lines indicate the actual range of success probability values obtained in the runs.

Figure 6 Percentage of successful iterations as a function of F_j



Success Percentage as a Function of M

Table 16 shows (in a format similar to Table 14) deviations from the mean for each run. In Table 16, the mean of the four values within a cell is presented in parentheses below the cell. This averaging was performed to cancel variations resulting from the Monte Carlo method. The results for individual runs are not indicative of exact task success probabilities due to the fact that each value in Table 14 represents only 100 simulations, each of which is based on a random effect. These averages indicate the obtained effect of M values on success probability for the task simulated. The expected directional trend is again obtained. Simulated teams whose members possess low stress tolerances tend to achieve less success. On the order of up to 4 per cent lower success than the mean is obtained in the upper portion of Table 16, and similar values of higher-than-average success is seen in the lower left and lower right portions of the table.

If one analyzes the M effects for the strike and tanker aircraft individually, the effect of the M_1 value (tanker) on the success probability is shown to be weak (Table 17).

Table 16

Difference from Average for Each Run for Each of Four F Values at Various M_1 and M_2 Values

M_2 \ M_1	1	1.5	2	3	4
1		-4.4/-1.1/-10.2/-0.7 (-4.1)			
1.5	0.6/-10.1/-3.2/-1.7 (-3.6)	1.6/-7.1/4.8/-0.7 (-0.4)		-0.4/-0.1/3.8/-4.7 (-0.3)	0.6/-2.5/1.8/0.3 (-0.2)
2					
3		-0.4/5.9/5.8/3.3 (3.8)		-1.4/-1.1/-4.2/-1.7 (-2.1)	-1.4/3.9/0.8/-1.7 (0.4)
4		1.6/5.9/-1.2/5.3 (2.9)		3.6/3.9/-1.2/3.3 (2.5)	-0.4/1.9/2.8/-0.7 (0.9)

Key:
F_1=F_2=
0.9/1.0/1.1/1.3

Table 17

Effect of M_1 Variations on Average Success Percentage (All M_2 Values)

M_1	F_j 0.9	1.0	1.1	1.3
1.5	90	76	49	12
3.0	91	76	50	10
4.0	90	76	52	10

This finding would be expected on the basis of the comparatively easy task role played by the pilot of the tanker aircraft. A somewhat greater effect of M_2 on success probability is shown in Figure 7. The trends indicated in Figure 7 suggest that success probability is relatively constant as M_2 increases above 2.0 to 2.5. Below these values of M_2, a decrease in success probability is observed as M decreases. This trend is also consistent with that obtained for the one-man model (Siegel and Wolf, 1950a; 1959b). However, in the one-man model success probability dropped by a factor of about one-half when M was decreased to a value of 1.5.

It is conjectured, however, that a significantly greater drop in success probability would have been experienced for the two-man model in this task if additional computer runs were made in the region of M_2 equal to 1.1 to 1.3.

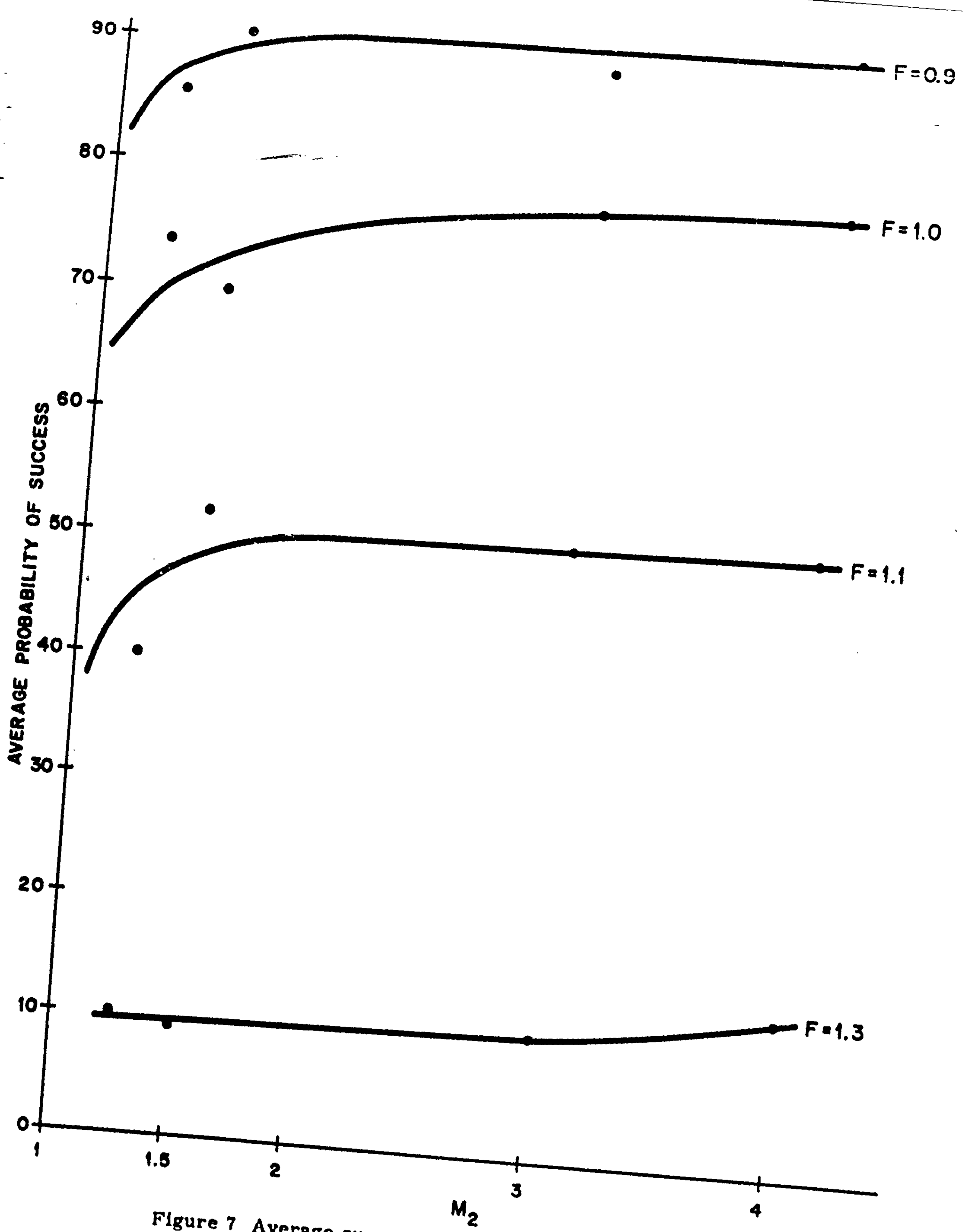


Figure 7 Average success probability as a function of M_2

Comparison with Outside Criteria

A primary aim of this study was to evaluate the model and determine conditions under which it agrees with actual events.

Outside criteria data were presented in Table 10. Table 10 indicated that 10 out of 16 actual flight trials, or 62.5 per cent, were successful. This figure is shown as a solid arrow on the ordinate of Figure 6.

If we accept the outside criteria value as accurate, Figure 6 indicates that the model produced similar task success probability when F_{12} = 1.05, or more accurately when F_{12} was in the range of about 1.01 to 1.08 (as indicated on the abscissa of Figure 6). These F_{12} values represent operators who are slightly slower than the average. It is noted that this value would be 1.0 from a model which yielded ideal results. However, if one assumes the universe of F8U-A4D in-flight refuelings to differ from the criterion sample obtained by as little as one unit (i.e., 9 or 11 successful attempts out of 16), then the model yields a value for F_{12} in the range 0.98 to 1.05 for one unit high and 1.02 to 1.11 for one unit low.

The actual confidence limits which can be placed on the outside criteria value may be based on the expression: $\sigma_p^2 = \frac{P(100-P)}{N}$. Even at the one sigma level, the confidence limits which may be placed on the outside criteria value are:

$$62.5\% \pm \frac{(62.5)(37.5)}{16} = 62.5\% \pm 12.1\%$$

This range is shown by the dotted arrows on the ordinate of Figure 6. If one assumes the range of values afforded by the one sigma confidence interval, the F_{12} range conforming to the criteria data would be 0.96 to 1.13. The F_{12} values discussed above (0.98 to 1.05) are well within this range.

A higher confidence level would yield a wider range of F_{12}. Thus, the results from the model agree with the outside criteria data in F_{12} values well within the limits of error of the outside criteria data.

Idle Time and Waiting Time

As would be expected from the nature of the task, the model indicated no idle time for either operator because of the non-occurrence of an outside event.

However, during the simulations, waiting time was encountered for both team members. A summary of the average waiting time (in seconds) for each run by M_1 and M_2 value is given in Table 18. The four values in the upper row of each cell of Table 18 indicate results for operator 1 for each F_j value investigated; the four values in the lower row indicate results for operator 2.

Here, again, no significant effect which can be attributed to a variation in M values was shown.

Table 18

Average Waiting Time (Seconds) for Each Operator for Each of Four F_j Values

M_2 \ M_1	1	1.5	2	3	4
1		2.3/ 2.7/ 3.0/ 3.3 12.8/14.6/15.8/18.7			
1.5	2.4/ 2.7/ 2.8/ 3.4 12.8/14.0/15.1/18.4	2.3/ 2.6/ 2.9/ 3.4 12.9/14.1/15.6/18.4		2.1/ 2.7/ 3.0/ 3.5 13.1/14.1/15.2/18.2	2.5/ 2.5/ 3.0/ 3.5 12.9/14.7/15.6/16.0
2					
3		2.4/ 2.6/ 2.8/ 3.5 13.1/14.3/15.3/18.5		2.4/ 2.7/ 2.9/ 3.7 12.6/14.5/15.4/18.7	2.3/ 2.5/ 2.9/ 3.8 12.9/14.7/15.1/18.5
4		2.4/ 2.7/ 2.9/ 3.5 12.9/14.3/16.1/17.7		2.4/ 2.4/ 3.0/ 3.2 12.8/14.2/15.6/18.1	2.3/ 2.7/ 2.9/ 3.4 13.0/14.2/15.2/18.5

Key:

F_1=F_2=
0.9/1.0/1.1/1.3

The average waiting time for all runs over all M values is shown in Table 19.

Table 19

Average Waiting Time for Various F_j Values

	F_j			
	0.9	1.0	1.1	1.3
Tanker	2.3	2.6	2.9	3.5
Strike	13.0	14.3	15.5	18.3

Table 19 suggests that the effects of F_j are approximately linear on waiting time for this task. As one might expect, faster operating teams, $F_1 = F_2 = 0.9$, are required to spend less time waiting for each other. Quantitatively, the model indicated the tanker to spend about 0.3 seconds more and the strike pilot to spend about 1.3 seconds more in waiting for every 10% decrease from "average" in team speed.

Time Remaining After Task Completion

An important use of the model could be to provide quantitative predictions on how much time remains to the operator after his task is completed. No field data were available against which to check these computed results for reasonable correspondence with reality. Although these data may have limited value in the validation of the model, they would be important when investigating or comparing proposed man-machine systems.

Since T_1 = 41.6 seconds and T_2 = 70.0 seconds, the strike pilot was the pacing team member, and the average time remaining for the tanker pilot is of no consequence in this task. The average time remaining after completion of the simulated task is shown in Table 20. The data in the upper portion of each cell represent the average time remaining after task completion considering only successful task simulations. The bottom row of each cell in Table 20 indicates average time remaining after all simulations.

These data indicate little overloading for the average (F = 1.0) and slightly faster than average (F = 0.9) pilot. However, according to the model, for the somewhat slower than average pilot (F = 1.1, F = 1.3) the time allowed for this task is tight and overloading present.

A plot of the average time remaining after successful simulations by F_j value is presented as Figure 8.

Table 20

Average Time Remaining After Task Completion (Successes Only, All Simulations)

M_2 \ M_1	1	1.5	2	3	4
1		12.9/8.4/6.3/4.0 11.1/6.2/2.5/0.4			
1.5	13.1/9.2/7.0/5.5 11.9/6.0/3.3/0.5	12.3/8.8/6.2/2.0 11.3/6.0/3.4/0.2		12.2/8.3/7.2/3.3 11.0/6.2/3.9/0.2	12.1/7.5/6.7/3.6 11.0/5.5/3.5/0.4
2					
3		13.2/8.6/6.1/2.1 11.9/7.0/3.4/0.3		11.1/8.5/3.9/2.2 9.9/6.3/1.8/0.2	12.2/7.7/5.1/2.2 10.8/6.1/2.6/0.2
4		11.1/8.6/5.5/3.1 10.2/7.0/2.7/0.5	Key: $F_1 = F_2 =$ 0.9/1.0/1.1/1.3	11.1/8.5/4.9/4.3 10.4/6.7/2.4/0.6	12.1/8.2/6.0/3.0 10.9/6.3/3.2/0.3

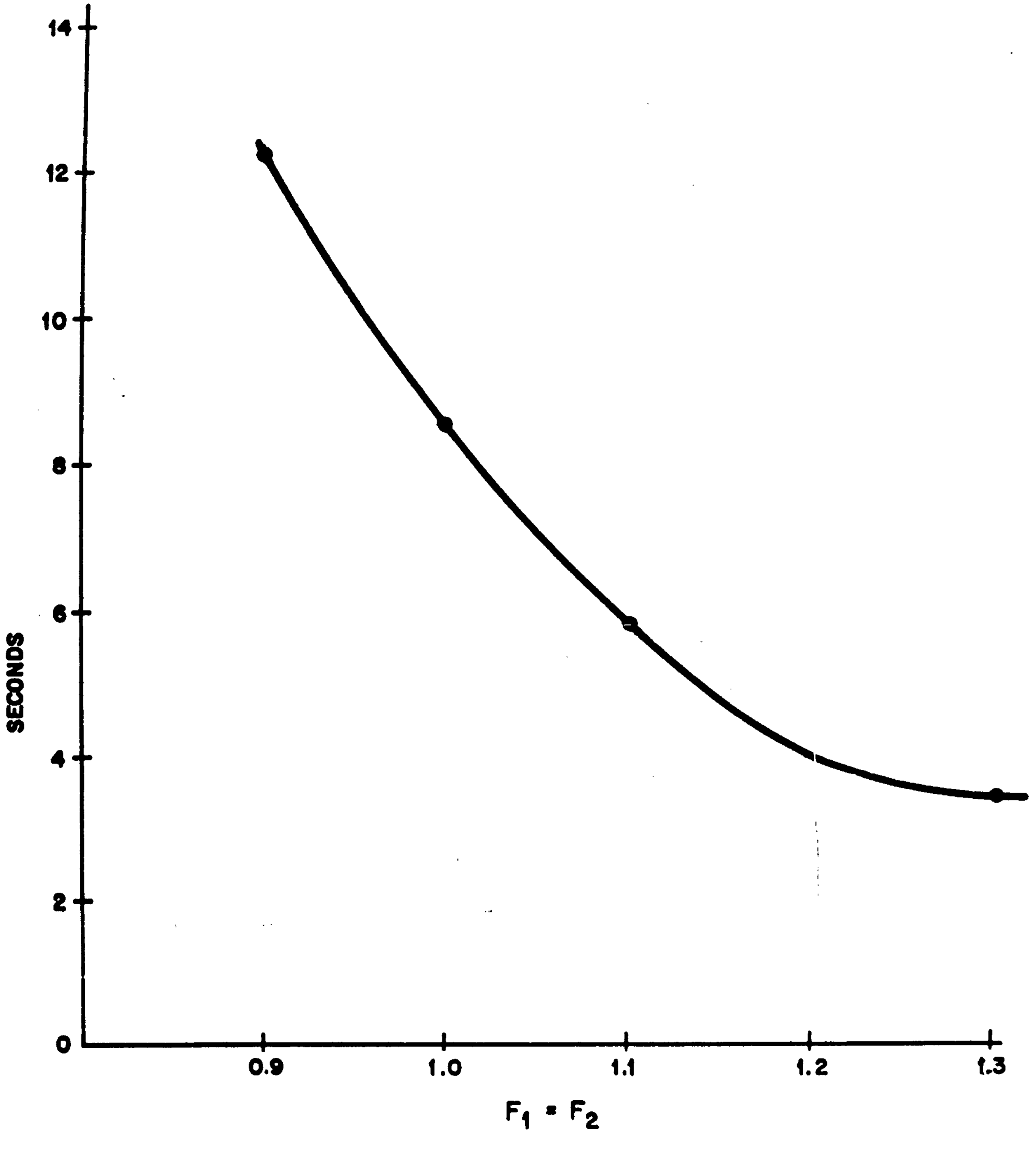


Figure 8 Average time remaining after successful task simulations

Terminal and Peak Stress

Tables 21 and 22 present respectively the average peak stress conditions and the stress conditions at the end of the selected computer runs. Data for the tanker are presented in the upper row of each cell and for the strike pilot in the lower row for each of the four F_j values. As expected, both the peak and the terminal stress values increased with increasing F_j values; this indicates that slower operators may be expected to build up greater stress than faster ones. This finding also reflects the fact that slower operators complete less work in a given time and consequently their $T_j - T_{ij}^U$ values (on which stress depends) are lower. It is further noted that over all M_j conditions, and in conformity with expectation, the strike pilot built up greater stress than did the tanker pilot. Review of the individual run data indicated that the peak stress condition occurred near the end of the runs, e.g., when the strike pilot closed in for actual probe insertion.

Table 21

Average Peak Stress

M_2 \ M_1	1	1.5	2	3	4
1		1.0/1.2/1.5/3.2 1.2/2.2/3.1/7.1			
1.5	1.0/1.1/2.2/4.0 1.2/1.8/4.1/5.0	1.0/1.1/2.0/3.0 1.5/2.0/2.8/3.9		1.1/1.2/1.7/3.7 1.3/3.0/4.6/6.5	1.1/1.4/2.0/3.5 2.1/2.1/4.0/6.2
2					
3		1.0/1.7/1.7/6.6 2.3/7.0/3.2/4.9		1.1/1.5/3.5/2.9 2.0/2.2/3.2/6.2	1.0/1.2/2.6/3.8 1.6/2.3/4.0/6.2
4		1.0/1.2/2.2/3.0 1.6/3.2/3.2/5.8		1.0/1.4/1.9/3.3 1.3/2.4/3.8/6.0	1.1/1.8/2.7/4.1 1.7/3.8/3.3/7.1

Key:

$F_1=F_2=$
0.9/1.0/1.1/1.3

Table 22

Average Terminal Stress

M_2 \ M_1	1	1.5	2	3	4
1		1.0/1.1/1.1/1.3 1.2/2.1/3.1/7.1			
1.5	1.0/1.0/1.1/1.1 1.2/1.8/4.1/5.0	1.0/1.1/1.2/1.4 1.5/2.0/2.8/3.9		1.1/1.2/1.5/2.3 1.3/3.0/4.6/6.5	1.1/1.4/1.8/2.6 2.1/2.1/4.0/6.2
2					
3		1.0/1.1/1.2/1.3 2.3/1.7/3.2/4.9		1.1/1.3/1.8/2.3 2.0/2.1/3.2/6.2	1.0/1.2/1.9/3.0 1.5/2.3/4.0/6.2
4		1.0/1.1/1.1/1.3 1.5/3.2/3.2/5.8		1.0/1.2/1.5/2.0 1.2/2.4/3.8/6.0	1.1/1.5/1.9/3.0 1.7/3.8/3.3/7.1

Key :

F_1=F_2=
0.9/1.0/1.3/1.5

Skipping of Non-Essential Subtasks

The model calls for either operator to skip each non-essential subtask whenever his stress exceeds unity. Table 23 presents a summary of the number of non-essential subtasks ignored by each simulated operator. Although reported in the final computer tabulations, Table 23 does not indicate which subtasks were ignored. The upper row of each cell applies to the tanker; the lower to the strike pilot. These data which are directly dependent on stress data are strongly influenced by the stress threshold. As an example, the results for the second operator over all M values are presented as Figure 9.

Figure 9 suggests, in disharmony with expectation, that operators with lower stress tolerances skipped fewer non-essential subtasks.

In conformity with expectation, Figure 9 also suggests that slower operators skipped more non-essential subtasks.

Table 23

Number of Non-Essential Subtasks Ignored Per Run of 100 Iterations

M_2 \ M_1	1	1.5	2	3	4
1		23/94/188/388 5/17/ 28/ 66			
1.5	20/85/166/368 7/28/ 45/ 79	22/73/186/384 6/24/ 35/ 72		28/73/177/381 8/23/ 37/ 80	24/105/211/356 11/ 28/ 48/ 78
2					
3		28/71/195/376 14/34/ 57/131		22/85/174/407 17/35/ 84/134	27/68/172/407 18/34/ 74/143
4		21/87/219/369 23/31/ 70/135		42/77/18 /336 9/41/ 75/129	37/99/175/385 15/33/ 59/133

Key:

$F_1 = F_2 =$
0.9/1.0/1.1/1.3

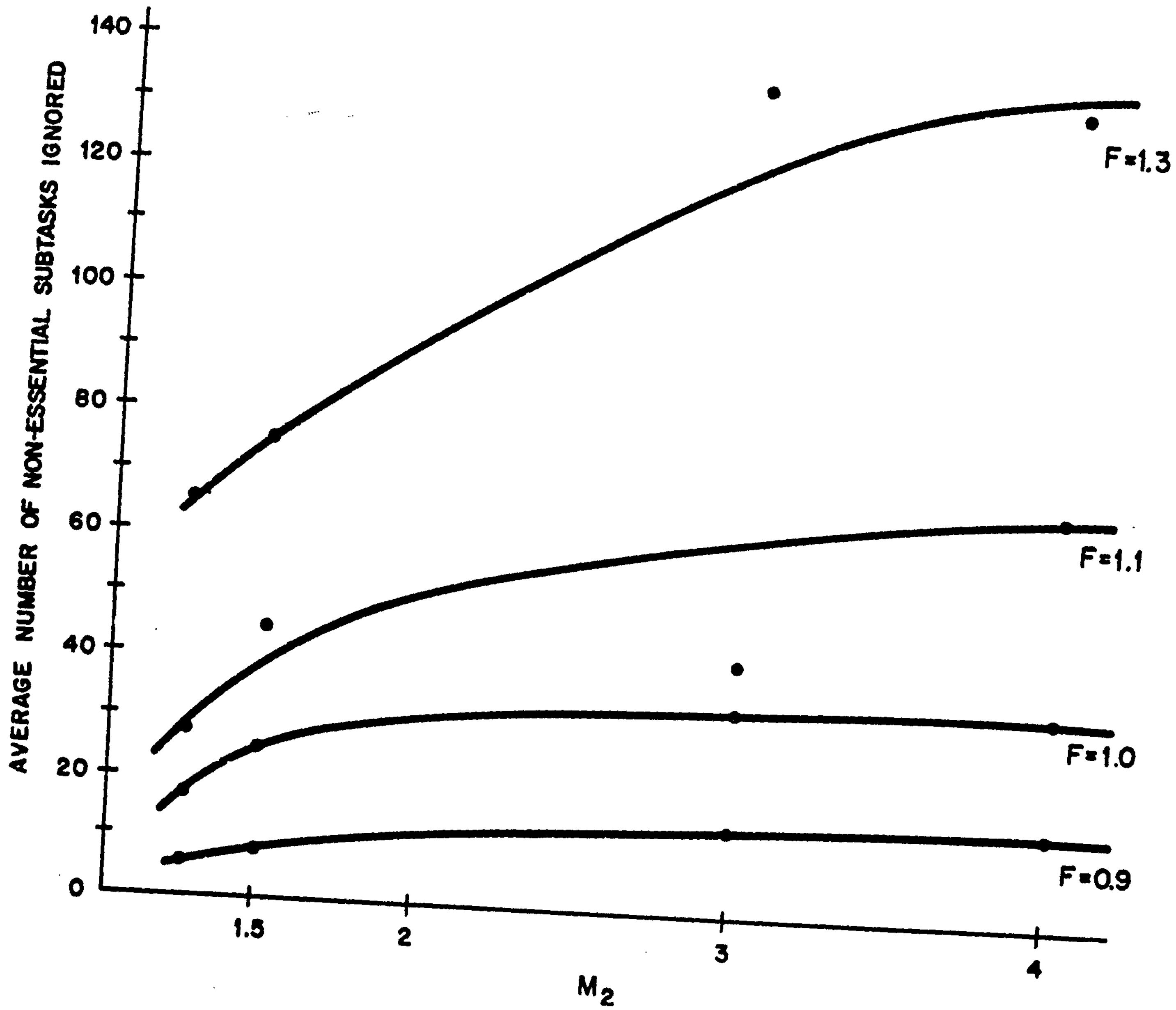


Figure 9 Average number of non-essential subtasks skipped by simulated strike pilots with various stress thresholds (M_2)

Average Terminal Cohesiveness

The cohesiveness index, as included, must be inversely interpreted. A high number indicates low cohesiveness; a low number indicates high cohesiveness.

The data on the mean cohesiveness of the operators at the end of the simulations are presented in Table 24. The tanker pilot's cohesiveness of zero or near zero merely indicates that either his stress at the early completion of his own work is zero or that the stress of the strike pilot at that early time in his task is zero. The data for the strike pilot, however, are significant. These data are affected both by M_2 and F values. A display of these data for all M_1 values is presented as Figure 10.

Figure 10, which plots the team cohesiveness function, defined as $C_{ij} = \frac{S_1S_2 - 1}{M_1M_2 - 1}$, indicates in conformity with expectation that faster teams ($F_j < 1$) are more cohesive, that higher stress thresholds yield better teamwork, and that a level of C_{ij} equal to unity occurs when $M_2 = 1.25$, $F = 1.0$ and for $M_2 = 2.25$, $F = 1.1$

<u>**Table 24**</u>

<u>**Average Terminal Cohesiveness**</u>

M_2 \ M_1	1	1.5	2	3	4
1		0.0/0.0/0.0/0.3 0.2/1.0/2.7/7.3			
1.5	0.0/0.0/0.0/1.8 0.2/1.0/3.1/5.0	0.0/0.0/0.1/0.2 0.5/0.8/1.7/3.4		0.0/0.0/0.0/0.1 0.1/0.4/1.4/3.9	0.0/0.0/0.0/0.1 0.2/0.4/0.9/2.8
2					
3		0.0/0.0/0.0/0.1 0.5/0.2/0.7/1.4		0.0/0.0/0.0/0.0 0.1/0.3/0.6/1.4	0.0/0.0/0.0/0.0 0.1/0.2/0.5/1.2
4		0.0/0.0/0.0/0.0 0.1/0.5/0.5/1.1		0.0/0.0/0.0/0.0 0.0/0.2/0.4/0.8	0.0/0.0/0.0/0.0 0.1/0.2/0.4/1.2

Key :

$F_1=F_2=$
0.9/1.0/1.1/1.3

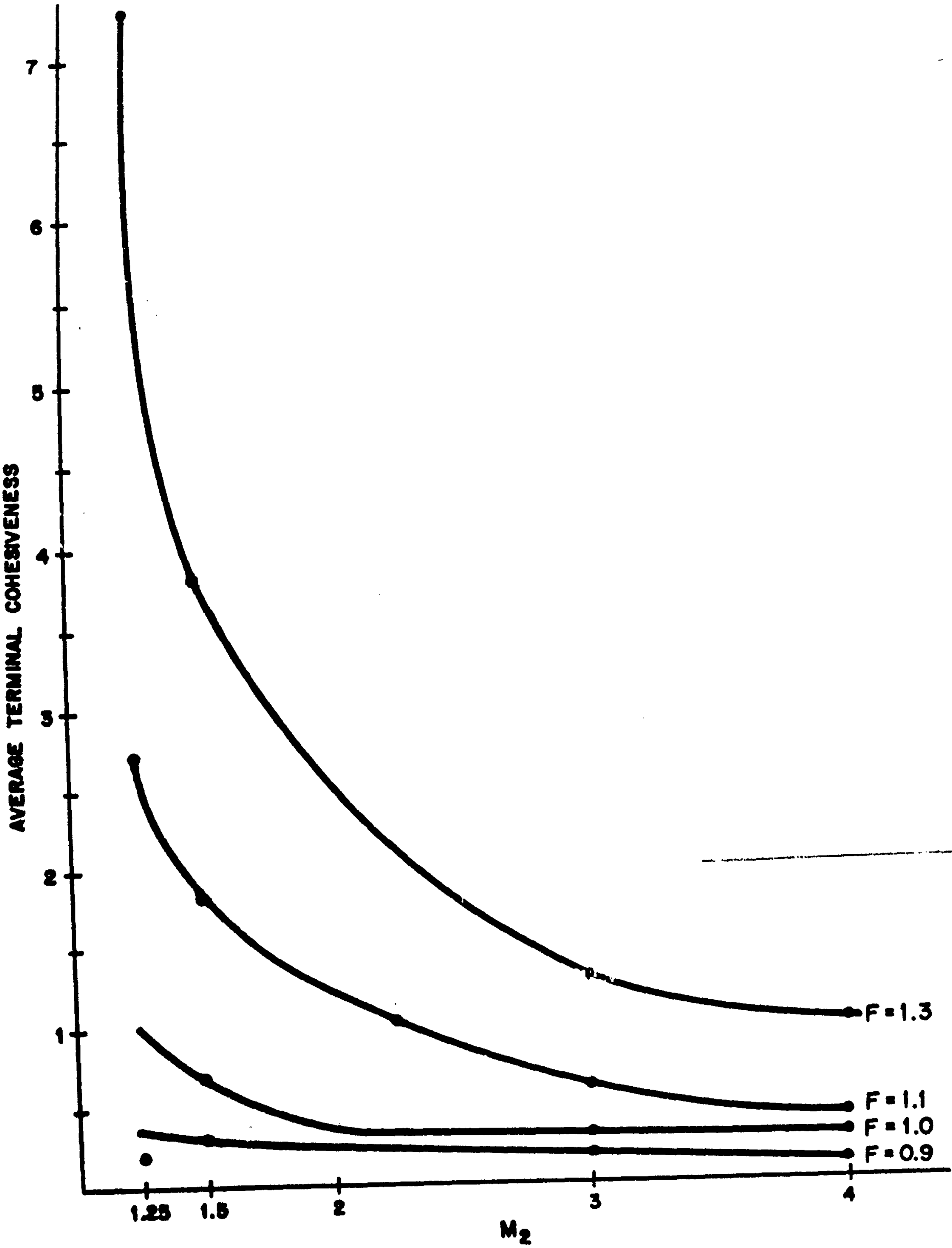


Figure 10 Average terminal cohesiveness as a function of M_2

CHAPTER VI

SUMMARY AND CONCLUSIONS

The development and application of a model to simulate system operation by a two-man team is described. The model is based on psychological data and concepts applied through digital simulation techniques. The purpose of this model is to answer questions, while a system is in the early design phase, such as the following:

1. Given a selected machine design, can an average two-man team be expected to complete successfully all actions required for task performance within the time limits given for each operator?

2. How does task or system success probability change for slower or faster teams and longer or shorter periods of allotted time?

3. How great a relative stress is placed on each operator during his performance and in which portions of the task are the operators overloaded or underloaded?

4. What is the frequency distribution of each operator's failures as a function of various relative stress tolerances and team member speeds?

5. For how much time is each operator idle while waiting either for the other operator or for some outside event to occur?

The model is based on the high-speed, general purpose digital computer. Tne computer operates on source data concerning subtask performance by average operators and on system parameters; using these, it simulates each operator by calculating values for and keeping track of items such as his performance time, task and subtask success or failure, stress, idle time, and cohesiveness with the other operator.

A buddy system in-flight refueling operation was simulated. This consists of 13 subtasks for the pilot of the tanker aircraft and 27 subtasks for the pilot of the receiver aircraft. A total of 4,400 simulations was performed, representing 44 combinations of pilot types.

Empirical comparison of the predictions from the model with outside criteria data on in-flight refueling success indicated reasonable concordance.

For the task simulated, the model was found to act rationally in that: [1] it showed a greater success percentage for faster teams and for teams with greater stress tolerances, [2] it showed greater idle time for faster teams and slower teams to be more overloaded during task performance, [3] it showed greater stress to be exerted on slower teams, [4] it showed slower teams to demonstrate less cohesiveness, and [5] it showed slower operators to skip more non-essential subtasks.

It may be concluded that in this initial validatory study the model yielded results which largely appear to conform with logic and with empirical data

Additional validatory studies, over similar and other classes of tasks, are required for greater confidence in the generality of the model.

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APPENDIX A

Appendix A briefly summarizes the major similarities and dif- derences between the two-operator model here described and the uni- operator model previously developed.

The two-man model is similar to the single operator model in that:

1. task success is based upon the time taken by the simulated operators to complete the task
2. a Monte Carlo technique is employed in the calculation of subtask execution times for each operator
3. consideration of operators of various speed capabilities is included
4. operators with various stress thresholds are considered
5. urgency and operator stress conditions are calculated prior to the performance of each subtask by the operators
6. the operators' failure to perform subtasks properly affects their stress level
7. capability to simulate idle time for either operator is included
8. simulation of decisions made by either operator is included to determine the course of action
9. simulation and computation is performed by a high-speed digital computer
10. results are obtained from computer recordings of task success probability, time remaining after completion, idle time, stress conditions, and subtask failures

The two-man model differs from the one-operator model in that the two-man model contains the following improved features:

1. capability to simulate either operator waiting for the other
2. improved method for computing normal deviates from pseudo-random numbers in the interval 0 to 1
3. capability to simulate communication between operators
4. capability to calculate a team cohesiveness indicator
5. capability to simulate decisions made by either operator
6. recording of additional data for analysis (e. g., peak stress values, identity of non-essential subtasks ignored by the operator, etc.)
7. automatic preparation of more extensive summaries of results by the computer (run summations as well as results of individual simulations and subtasks)
8. dependence of operator performance on the stress value of his partner

In addition to these improved features, the technique of preparing computer instructions is improved by the use of automatic programming methods and a higher speed computer is utilized.